NaviRadar: A Tactile Information Display for Pedestrian Navigation

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ABSTRACT

We introduce NaviRadar: an interaction technique for mobile phones that uses a radar metaphor in order to communicate the user's correct direction for crossings along a desired route. A radar sweep rotates clockwise and tactile feedback is provided where each sweep distinctly conveys the user's current direction and the direction in which the user must travel. In a first study, we evaluated the overall concept and tested five different tactile patterns to communicate the two different directions via a single tactor. The results show that people are able to easily understand the NaviRadar concept and can identify the correct direction with a mean deviation of 37° out of the full 360° provided. A second study shows that NaviRadar achieves similar results in terms of perceived usability and navigation performance when compared with spoken instructions. By using only tactile feedback, NaviRadar provides distinct advantages over current systems. In particular, no visual attention is required to navigate; thus, it can be spent on providing greater awareness of one's surroundings. Moreover, the lack of audio attention enables it to be used in noisy environments or this attention can be better spent on talking with others during navigation.

ACM Classification: H.5.2 [Information Interfaces and Presentation]: User Interfaces – Input devices and strategies; Prototyping. H.1.2 [Models and Principles]: User/Machine Systems – Human Factors.

General terms: Design, Human Factors, Experimentation.

Keywords: Pedestrian navigation, tactile feedback, radar.

INTRODUCTION

Mobile navigation, which has become very popular in the last decade, started with availability of affordable satnavs and is now widely used on mobile phones for pedestrian navigation, for example, Nokia's Ovi Maps and Google Maps. The communication of navigational information when walking via visual information or spoken instructions provide certain, self-evident, disadvantages when it comes to the user's attention (awareness of the traffic and the user's ability to focus on the walking task itself) and the user's environment (information clarity in noisy environments and obtrusiveness in a social context).

We present a navigation technique using only tactile feedback, provided by a single vibrator on a mobile device, to communicate directional information using a radar metaphor. Distinct tactile feedback is provided when the constantly rotating radar sweep crosses the current direction (D_C) and the direction in which to travel (or desired direction, D_D) as illustrated in the Figure 1.

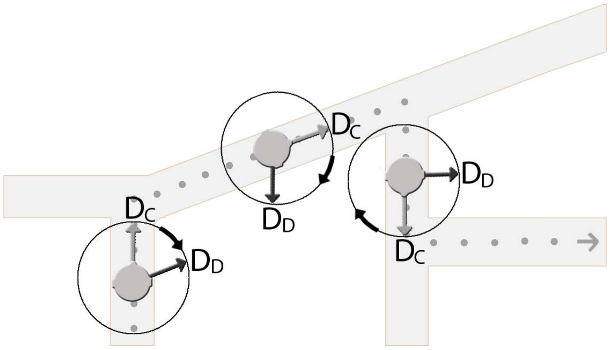

Figure 1. NaviRadar concept illustrating a path where the user has to turn right, right again and left (D_C – current direction, D_D – desired direction)

The user is able to differentiate between the two directions as they are communicated via different tactile patterns called tactons [3]. Our user studies showed that the participants quickly learned the correspondence between the radar sweep time and the angle difference between D_C and D_D. The mobile phone screen could provide a radar visualization; however, the intended use is that the user walks without looking at the screen, rather using predominantly the tactile feedback to navigate. Therefore, NaviRadar provides unobtrusive navigation, which enables the user to focus on the walking task, pay attention to the traffic, and to talk with others.

This paper reports two different studies. Firstly, the overall concept and different vibration patterns are evaluated. Secondly, NaviRadar is compared with the provision of navigational information via spoken instructions and PocketNavigator – another approach providing navigational information via tactile feedback. The first study showed

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that all participants easily understood the NaviRadar concept. It also demonstrated that communicating the current direction with one vibration and the desired direction with two vibrations in close succession is the most accurate and preferable approach. Furthermore, it was shown that changing the intensity of the vibrations can effectively be used to communicate the distance to the next crossing. The second study was performed outdoors and participants were required to navigate along predefined routes. The results show that NaviRadar achieves a similar navigation performance in a realistic setting when compared with spoken navigation information. A comparison with PocketNavigator shows advantages of NaviRadar with regard to navigation performance.

BACKGROUND

Route instructions provided by mobile devices are typically communicated via: spoken instructions, text, 2D route sketches, routes on 2D or 3D maps, and combinations of the previously mentioned possibilities [8]. A large amount of information can be communicated via the screen of the mobile device, but it is rather impractical to look at the screen while walking. This is due to the fact that it is difficult to read text and recognize visual route instructions due to the constant movement of hand, head and body [19]. Furthermore, it becomes difficult to concentrate on the walking task itself while in "heads-down" mode as this affects the awareness of other pedestrians, lamp posts or the traffic [2]. This leads to the fact that users immersed in the usage of their mobile phones are more likely to walk into other people or objects, or to stumble [12].

The usage of spoken instructions provides several advantages as the visual channel is not required to communicate route instructions. Therefore, visual attention can be solely dedicated to observing the environment. However, spoken instructions could have a high level of intrusion for others nearby as the feedback delivery time cannot be controlled. Furthermore, spoken instructions may not be received in noisy environments, such as a busy crossing or during a conversion [6].

The usage of tactile feedback for the provision of navigation information has been widely investigated in recent years. One such reason for this fact is that this feedback channel does not disturb the user's primary tasks (walking, talking or awareness of traffic, other pedestrians and objects) as much as visual and auditory information do. Therefore, tactile user interfaces are, in general, less distracting in terms of divided attention and disturbance than visual and auditory interfaces [3,18]. A range of different parameters, such as frequency, amplitude (intensity), duration, timing and rhythm, can be changed in order to create different tactile patterns [3]. With multiple vibrators, further parameters, such as location of vibration [2], movements or speed [6], could be manipulated.

Several projects used two vibrators to communicate "left" and "right" to the users. In previous work, such vibrators were attached to the left and right hand [2], thumb and forefinger [5] or left and right shoulder [14]. Other prototypes involved several vibrators attached to a belt [18] or vest [17] to communicate directional information via the location of the vibrators. Those approaches provide a very efficient, simple, and easy to understand way to communicate directional information, but they require special wearable equipment. Sahami at al. present a mobile device with 6 different vibration motors that could be used to communicate different directions. Such work demonstrated that is possible to communicate directional movements via patterns such as Top-to-down or Right-to-left [16]. We decided to use only one vibrator to communicate the NaviRadar patterns so standard mobile phones which have just one vibrator can be supported.

Another approach is to provide concrete navigation information via tactile feedback from one single mobile device with built-in vibrator. Here, directional information must be encoded via distinguishable tactons. The approach presented by Lin et al. uses three different rhythms to communicate *Turn Right, Turn Left* and *Stop* [9]. The rhythms were also played in two different tempos in order to communicate the distance to the next crossing. The PocketNavigator is a similar approach, that uses the different tactons shown in Figure 2 to indicate the user to go straight on (two short pulses), to turn around (three short pulses), to turn left (long vibration followed by short vibration), and to turn right (short vibration followed by long vibration) [11]. This system also supports the communication of different angles. For each side, three different angle areas can be indicated by adjusting the length of the longer vibration.

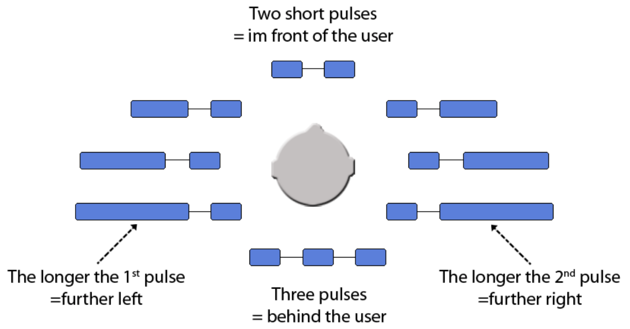


Figure 2. PocketNavigator tactons communicate direction [11].

The advantage of NaviRadar when compared with the previous two systems is the possibility to communicate arbitrary directions in the full range of 360°, rather than only left and right as in Lin at al.'s system, or the three angles areas per side as in the PocketNavigator. Moreover, only one pattern is used to indicate the desired direction (cf. PocketNavigator uses different patterns for indicating go ahead and turn around).

Robinson et al. presented an approach where the user receives tactile feedback if they point in the direction of the destination [13]. The system does not provide turn-by-turn instructions, though it does help the user to travel in the correct direction. However, it is an interesting option for tourists who wish to travel to a specific place in addition to exploring the area along the way.

The Rotating Compass [15] provides navigation instructions via the combined use of a public display and a mobile device. It uses a public display that constantly iterates over available direction options, indicating them publicly to all bystanders. It is the user's mobile phone that notifies each user their individual direction via a short vibration when the correct direction is indicated. However, it does require a public display to be installed at every crossing – an assumption that is currently impractical.

COMPARISION OF TACTILE PATTERNS

The goal of the first experiment was to analyze whether the NaviRadar concept could be easily understood by users and which tactile patterns offer the best performance when communicating distinct directions (current and desired) and distances (close and far).

Introducing the Compared Tactile Patterns

We conducted preliminary tests to analyze which tactons could potentially be used to communicate the direction to go at the next crossing and the distance to it. From these tests, we concluded that changing the duration, intensity, rhythm and roughness of the vibration are good candidates and should be tested in our study.

Table 1 shows the five different vibration patterns compared in the study. The icons in the table visualize a situation where the user is currently going straight and has to turn right at the next crossing. The circle represents the radar metaphor, the arrow the direction of the rotational sweep and the thin rectangle facing ahead the current direction. The height of the rectangle shows how strong the vibration is and the width shows the duration of the vibration. We decided to always use a short (50ms) and strong vibration to communicate the current direction as this is the most simple and easy to perceive tacton.

The first row of Table 1 shows three different patterns which communicate the difference between the current direction (D_C) and desired direction (D_D) via the different duration of the two tactons (D_C: 50ms, D_D: 200ms). Within this first row, there are three different ways in which distance can be indicated. *DurInt* communicates the distance to the next crossing using intensity (intense when close and weak when distant). *DurRhy* uses two different rhythms (close: two pulses, distant: one pulse). *DurRou* uses roughness (close: rough, distant: normal).

The second row shows *IntInt* where direction is indicated using a buildup of vibration intensity from D_C where this intensity finishes at D_D (vice versa when communicating a direction on the left hand side). The final strength of the vibration is also used to indicate the distance. The third row shows *RhyInt* where the current direction is communicated via a single vibration and the desired one via two vibrations in quick succession.

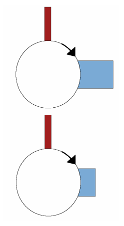
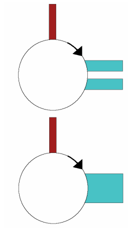
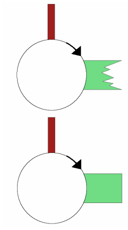
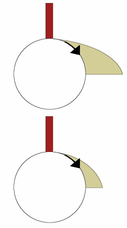
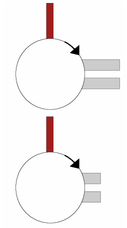
		Distance		
		Intensity	Rhythm	Roughness
Direction	Duration	 DurInt	 DurRhy	 DurRou
	Intensity	 IntInt		
	Rhythm	 RhyInt		

Table 1. Tactile patterns (upper ones: close to crossing, lower ones: distant)

When using intensity and rhythm to communicate the direction, it is not practical to use rhythm or roughness to communicate the distance. Those missing combinations have been studied in our earlier informal tests and were not seen as good candidates. As one example, it is very difficult to feel a change in intensity when applying a rhythm or roughness simultaneously.

Participants

12 paid participants, 6 female and 6 male, took part in the first user study. All of them were either students or employees of Lancaster University, were aged between 19 and 32 (mean = 21.3) years, and are not involved in the presented research. On average, they rated themselves with a high experience with computers and medium-high experience with mobile phones (scale used: 1=none, 2=poor, 3=medium, 4=high, 5=expert). All of them had used a satnav before, though only 4 had used a map application on a mobile phone.

Apparatus

One EAI C2 tactor [1] was attached on the backside of a Motorola Milestone as show in Figure 3. The C2 tactor is a small and light tactile actuator that provides a strong, localized sensation on the skin and has been widely used in previous research [7]. It is able to provide richer feedback when compared with the built-in vibrator of the Motorola Milestone and parameters such as roughness and intensity can be controlled easily. Figure 3 shows the positioning of the tactor on the phone and where fingers are placed during the study. The C2 actuator was connected to a FiiO E5 headphone amplifier. This was, in turn, connected to the audio out port of a Sony Vaio NR11Z controlling the C2 tactor with a 250 Hz signal. The intensity of the vibration was controlled via the amplitude of the audio signal and roughness was generated by amplitude modulation.

Figure 3. Motorola Milestone with C2 tactor.

Experimental Design

The experiment used a within-subjects design with three independent variables: **tactile pattern** containing the five levels from Table 1 *(DurInt*, *DurRhy*, *DurRou, IntInt*, *RhyInt)*, **direction** (30°, 60°, 90°, 135°, 180°, 225°, 270°, 300°, 330°) and **distance** containing two levels: *close* (to a crossing) and *distant*. The measured dependent variables were their reported direction and distance.

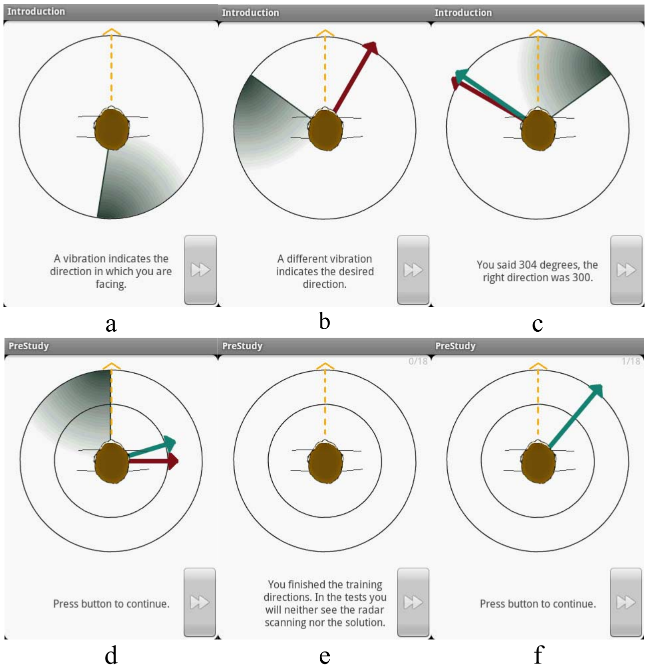
The Study Procedure

The participants took part in the study individually and the study was performed in a laboratory setting. The study procedure began with a demonstration of the hardware used and how they should hold the mobile phone. Afterwards, they took the position indicated in Figure 4 in which they held the mobile phone in their left hand and controlled the study application (running on the laptop) with the mouse in their right hand.

One important aim of the study was to analyze how accurate participants could recognize the indicated direction. Their task was to select an orientation on a circle which can be executed much more accurately with a mouse when compared with finger-based input on a mobile phone, so the test application (implemented in Android) was running on an emulator on the laptop instead of on the phone. The test application automatically presented the different test conditions to the user and logged all user input for further analysis.

Figure 4. Study setting and participant interaction position

Initially, the participants were presented with a training application using a few animations to explain the overall concept of NaviRadar (Figure 5a&b). Following this, several directions were communicated and the participant was required to indicate the desired direction D_D with a mouse click on the circle (marked with a turquoise arrow). In response, the system provided them feedback regarding how correct the estimation was (red arrow in Figure 5c). They were also trained how to report a close (touch point on inner circle, Figure 5d) and distant crossings (touch point outer circle). During tasks, participants were able to ask the instigator questions.



Introduction

A vibration indicates the direction in which you are facing.

Introduction

A different vibration indicates the desired direction.

Introduction

You said 304 degrees, the right direction was 300.

PreStudy

Press button to continue.

PreStudy

0/18

You finished the training directions. In the tests you will neither see the radar scanning nor the solution.

PreStudy

1/18

Press button to continue.

Figure 5. Test application running on a laptop.

Following the training stage, the participants were asked to wear headphones playing a mixture of white noise and typical street noise [4]. These were used to block any sounds generated by the C2 tactors. Then, they were presented with one of the five tested patterns. This started with an introduction into the pattern being based on textual information and an illustration. Then, they were presented with two close and two distant crossings where they selected distance (select inner or outer circle) and direction (location on circle) and received feedback regarding the accuracy of their selection. Once the training for this pattern was completed, they were required to define direction and distance for 18 different settings (2 distances x 9 directions) for this particular pattern. Here, no radar sweep was shown (Figure 5e) and they did not receive any feedback from the application regarding the correctness of their selection (Figure 5f). Then, they were asked 7 questions regarding this particular pattern pertaining to understandability, clearness, intuitiveness, mental effort and their personal rating. Next, the training for the following pattern started. The sequence of presented tactile patterns was counterbalanced using a Latin square, and the sequence of directions and distances was randomized for each test.

Results

The results of the study were analyzed in order to see whether the NaviRadar concept can be efficiently used to communicate direction and distance. Moreover, the results were used to see which tactile pattern leads to the best results. Unless otherwise stated, all effects will be reported at a .05 level of significance.

Recognition of Direction

The most important aspect of a navigation system is that it shows the user the correct direction. Figure 6 shows a strong relationship between the angle that has been communicated (outside of the circle) via the tactons and the mean angles recognized by the participants in the study (inside of the circle). It considers all tactile patterns, distances and participants. For instance, participants reported on average an angle of 22° when an angle of 30° was communicated by the system. Interestingly though, the participants always perceived the communicated angle to be closer to the current direction as it actually is.

When investigating the deviation of the reported angles, a relatively high variance can be seen. Table 2 shows that the mean deviation from the correct angle ranged from 37.5° to 50.5° when comparing the different tactile patterns. Mauchly's test violated the assumption of sphericity for the main effect of *pattern* ($\chi^2(9) = 17.53$); therefore, degrees of freedom were corrected using the Greenhouse-Geisser correction ($\varepsilon = 0.50$). The main effect of *pattern* was significant ($F_{1.99, 21.94} = 5.49$). Bonferroni post-hoc tests revealed a significant difference between patterns *IntInt* and *RhyInt* showing that when *RhyInt* is used, input values are perceived more accurately.

The participants needed on average 8.6s to 12.7s to report the direction and distance. This implies that they needed circa 3 to 4 rotations to make a decision as the time of circulation was 3 seconds. Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(9) = 42.69$). Applying a Greenhouse-Geisser correction ($\varepsilon = 0.50$), the ANOVA revealed that input time was significantly affected by the main effect of *pattern* ($F_{1.42, 15.82} = 4.64$). More time was needed using *IntInt* than when patterns *DurInt*, *DurRhy* or *DurRou* were used.

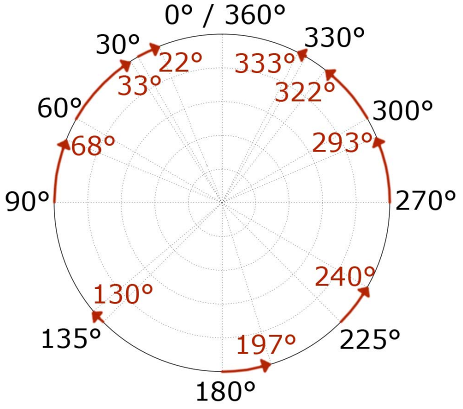


Figure 6. Relationship between communicated angle to go and mean reported angle.

The participants were also asked how clear, understandable and intuitive the representations of direction for the different tactile patterns were. The corresponding results can be seen in Table 2 as well. Friedman's ANOVA showed that ratings for clearness were significantly affected by the pattern used ($\chi^2(4) = 16.89$). Post-hoc tests revealed that using *IntInt* affected the rating negatively compared to *DurInt*, *DurRhy* and *RhyInt*. Differences regarding intuitiveness were not significant.

	DurInt	**DurRhy**	**DurRou**	**IntInt**	**RhyInt**
Mean deviation (SE) (in degree)	50.5 (5.1)	41.9 (4.3)	39.1 (4.5)	54.2 (5.5)	37.5 (4.8)
Mean input time (SE) (in s)	8.6 (1.0)	7.9 (0.7)	8.9 (0.8)	12.7 (2.2)	8.8 (0.8)
Clear and under-standable (SD)	4.0 (0.8)	3.9 (0.8)	3.6 (0.8)	2.6 (0.9)	4.1 (0.8)
Intuitive (SD)	4.0 (0.5)	3.8 (1.0)	3.6 (0.7)	3.2 (1.1)	3.9 (0.7)

Table 2. Recognition of angle, input time, subjective ratings (scale from 1 – strongly disagree to 5 – strongly agree).

When analyzing the results, one can see that the pattern responsible for communicating direction via rhythm and distance via intensity (*RhyInt*) had the lowest mean deviation from the given angle. In addition, it had the second lowest mean input time, was considered as the most clear and understandable one, and was rated second best with respect to intuitiveness.

Recognition of Distance

Table 3 shows the percentage of correctly recognized distances and subjective ratings of distance representations. *DurInt* and *DurRhy* performed excellent as more than 90%

of all distances were correctly recognized. *RhyInt* provided even better results with a recognition rate above 95%. The assumption of sphericity had not been met ($\chi^2(9) = 19.21$), so a Greenhouse-Geisser correction was applied ($\varepsilon = 0.69$). The ANOVA shows that the main effect of *pattern* significantly affected these differences ($F_{2.75, 30.26} = 11.07$, $p < 0.001$). Bonferroni-corrected post-hoc tests reveal that *DurInt* and *RhyInt* cause significantly less errors concerning distance than *DurRou* and *IntInt*. Looking at the mean ratings, *RhyInt* placed second best when considering how clear and understandable distance was perceived and placed second when considering the intuitiveness of the direction indication.

	DurInt	DurRhy	DurRou	IntInt	RhyInt
Correct distance	90,3%	90,3%	59,7%	69,0%	95,8%
Clear and understandable (SD)	3.8 (0.9)	4.6 (0.5)	3.1 (1.1)	3.4 (0.9)	4.1 (0.8)
Intuitive (SD)	4.0 (0.6)	4.3 (0.5)	3.2 (1.2)	3.6 (0.8)	4.0 (0.8)

Table 3. Recognition of distance and subjective ratings (scale from 1 – strongly disagree to 5 – strongly agree) for distance.

Mental effort

Participants were also asked to rate the mental effort required in order to understand the encoded direction and distance for a recently completed test. Mental effort should be as low as possible to allow one to understand the presented information – especially as walking and taking care of other pedestrians, traffic and objects is the main task. The results as shown in Figure 7 indicate that *DurRou* and *IntInt* require a relatively high mental effort where *DurInt*, *DurRhy* and *RhyInt* performed best. These ratings differ significantly regarding the pattern they describe ($\chi^2(4) = 27.21$, $p << 0.01$). Post-hoc tests show that *IntInt* causes a significantly higher effort to interpret the presented information than *DurRhy* and *RhyInt*, the last performed significantly better than *DurRou* also.

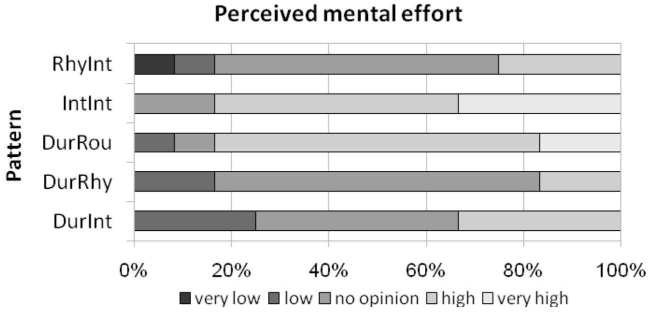


Figure 7. Ratings of perceived mental effort.

Subjective Preferences

At the end of every post-questionnaire, participants were asked to rate each pattern on a scale from very bad to very good. *RhyInt* received the best rating for 8 out of 12 participants. *DurRhy* and *DurInt* were perceived best by 7 and 4 participants, respectively. The other patterns achieved one or zero "very good" votes. As worst, 9 of the 12 participants rated *IntInt*. *DurRou* received 5 votes. The other patterns never achieved the worst result.

Training effect

The importance to not only analyze experimental conditions such as vibrotactile parameters but also training effects for vibrational feedback on results has been mentioned in [10]. Hoggan and Brewster [7] show the results of training runs where participants were presented 18 different tactons twice per run. On average, it took three training sessions before participants were able to identify the tactons with recognition rates of 90% or higher.

Taking these findings into consideration, we analyzed how the average deviation regarding the difference between indicated and reported direction to travel changed over the 6 different runs. Figure 8 shows that the average deviation improved from 55.9° in the first run to 36.7° in the last run. This is a reduction of more than 30%. Pearson r for the correlation between order and deviation is -0.14. This indicates that the more participants became familiar with the vibrations, the smaller the error became.

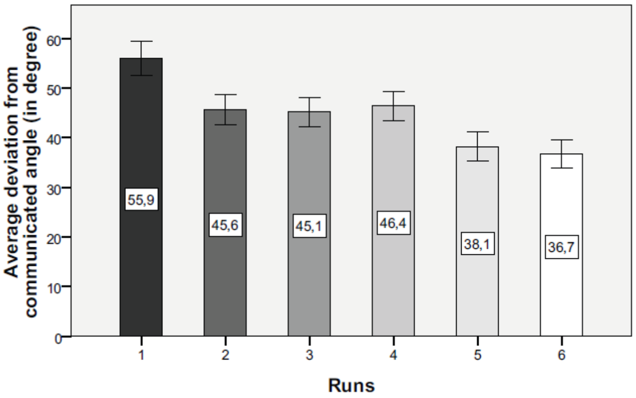


Figure 8. Effect of training on average deviation of reported from given angle (Error bars: +/- 1 SE).

No statistical effects were measurable regarding improvement of recognition of distance and input time due to repeated usage.

Participants' Comments

The participants generally liked the concept of encoding the distance via the intensity of the vibration as they linked it to the model of sound that gets louder the closer it is (*DurInt*). Similarly, they liked the idea of using rhythm for the encoding of the distance (*DurRhy*) and often said that the double pulse feels like a warning that they have to turn shortly. The perceived intensity of a tacton is also increased by an increased roughness of the signal and, therefore, the increase of the roughness when nearing a crossing was also well-perceived (*DurRou*).

Communicating the direction via a change in intensity was disliked by the participants as they found it difficult to recognize the communicated direction. Reason for this is that they were required to constantly pay attention when the vibration has its peak and stops (*IntInt*). *RhyInt* was also well-perceived and performed best overall. Therefore, it was selected for the second study.

Results for RhyInt

Our results show that rhythm is the most effective way to create distinct vibrations for both distance and direction. Therefore, this parameter should be used to communicate the most important information – namely direction – whereas for distance, intensity proved to be most efficient. Consequently, we will discuss further results for *RhyInt,* which performed best in the first study. Figure 9 shows the locations of the reported angles through color coding and shows the mean deviation of the reported angles through the central angle and radius of the pie slice.

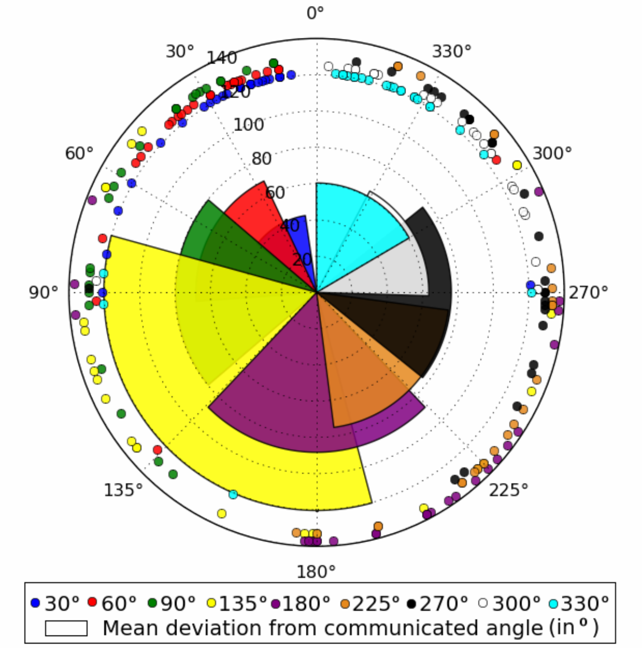


Figure 9. Location of reported angles and mean deviation of reported angles from indicated angles for *RhyInt*.

For instance, the mean deviation of the angle 30° was 21.4°. This implies the high likeliness that the users perceive this angle in the interval 30° ± 21.4°. Therefore, the corresponding pie in Figure 9 has a radius of 42.8 (2 x 21.4°) and a central angle of 42.8°. The reported angles for 30°, 60°, 300° and 330° are clustered around those angles, indicating that participants recognized the directions accurately with only slight deviations, which in turn leads to small pies. In contrast, reported directions for 135°, 180° or 225° are spread over greater intervals and corresponding pie slices are of a bigger size.

Figure 9 shows that directions around the back of the user (ranging from 135° to 225°) are recognized worse than directions in front. We expect this to be due to the fact that there are longer interval durations between D_C and D_D for the directions behind the user. Consequently, they are harder to estimate. A solution could be to increase the rotation speed; thus, decreasing the duration between signals.

Figure 10a-c shows different scenarios where NaviRadar provides sufficient accuracy. The red pie slices indicate the mean deviation for a given angle. Figure 10d shows a scenario where an error could occur easily, because pies for different directions overlap indicating that the user could consider an indication to show a wrong direction. However, as soon as the user turns towards the rough direction, the situation changes, and instead of three left turns, a straight as well as slight turns to the left and right are available (see Figure 10e). This leads to greater separation of the deviation areas as the direction "straight on" is distinctly indicated by a single pulse because the two directions D_C and D_D coincide, and deviation areas of the slight turns do not overlap. A method to prevent errors emerging from overlapping areas could be to indicate the ambiguity with a special vibration signal; in this case, the user would have to view the phone screen. But this would not occur frequently as, in practice, there are not that many crossings where several paths point in a similar direction.

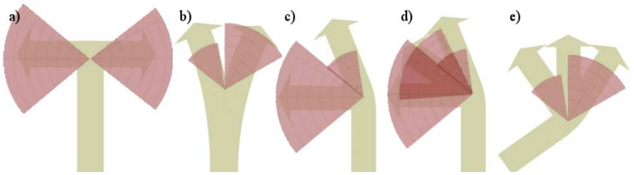


Figure 10. Practical implications of deviations of *RhyInt*.

COMPARISION IN CONTEXT

An outdoor study was conducted in order to test the concept of NaviRadar in a realistic setting where it would be compared with two other navigation systems. The navigation with all three systems relied solely on nonvisual information provided via either tactile or audio feedback. This allows the user to easily chat with others and to concentrate on traffic, other pedestrians and objects (such a lamp posts, which could be easily walked into when looking at the mobile phone screen).

Compared Systems

There were choices for comparison with NaviRadar. We omitted the work by Lin et al. as it supports only the communication of left and right [9]. We also omitted the work by Robinson et al. as it requires active scanning of the desired direction and its obtrusiveness as the user has to explicitly point at several directions [13]. We decided to compare NaviRadar using the *RhyInt* tacton with PocketNavigator as it also can communicate several different directions unobtrusively via tactile feedback. We also compared it with a system offering spoken instructions known from commercial navigation systems.

We did not compare NaviRadar with a system offering visual feedback as it is clear that the participants can navigate proficiently with it (e.g. in terms of task completion time and error rate). However, the user must divide their visual attention between mobile device and environment. The latter is a significant and inherent disadvantage as the user cannot always concentrate visually on the environment, traffic and other pedestrians.

PocketNavigator

PocketNavigator is a map-based pedestrian navigation application available in the Android market that also offers hands free navigation via tactile feedback [11]. It does provide turn-by-turn instructions but these are provided only when the user reaches the next turn. Duration of the pulses is used to indicate direction as shown in Figure 2.

There are several conceptual differences between NaviRadar and PocketNavigator. Firstly, PocketNavigator uses different patterns for the different directions. This might make it more difficult to learn. Consequently, one could assume that NaviRadar can communicate different directions (e.g. 60° vs. 90°) more accurately as they are communicated via the time difference between the two vibrations, not by the duration of one single vibration as used by PocketNavigator.

Spoken Instructions

NaviRadar has been compared to the approach used in Ovi Maps and Google's pedestrian navigation, which offers visual, tactile and spoken instructions to guide the users. It can be used easily while walking and without using the visual information provided. Therefore, the user holds the phone in one hand while walking and is informed via a short vibration that spoken audio instructions (e.g. "turn left in 50 meters") will follow soon. In response, the user can then bring the phone to their ear in order to hear the spoken instructions more clearly.

For the study, the timing and vocabulary used in Ovi Maps are taken. It is widely used and preinstalled on many Symbian phones. Google Navigation for pedestrians had not been released when the study was conducted; however, the principle of combined feedback is the same.

Apparatus

A Motorola Milestone running Android 2.1 was used to re-implement the features of PocketNavigator and Ovi Maps required for the study. As the mobile phone screen was not used during the study, none of the visual aspects of those systems have been implemented.

The decision for reimplementation was done because of health and safety considerations and a risk assessment. Because of this, we had to perform the study in a pedestrian area without any traffic on our University campus. The streets of this area are not included in any available mobile navigation system. Therefore, we had to re-implement PocketNavigator and Ovi Maps as it is not possible to add our own map of the University campus. We analyzed PocketNavigator and Ovi Maps very carefully to make sure that our re-implementations are as similar as possible when compared with the original implementations.

As our first study identified the optimal tactons using the C2 tactor, we used it once more for the comparative study using NaviRadar. Unfortunately, the C2 tactor that was attached to the backside of the phone heavily influenced the built-in compass. Accordingly, we had to place an external compass 32 cm from the tactor using an extension mounted to the phone. This external compass communicated via Bluetooth with the mobile phone and offered accuracy comparable to the built-in compass.

Participants

12 participants, 6 female and 6 male, took part in the study. None of them had been participating in the previously reported study. Their age ranged from 19 to 51 (mean = 28.3) years and are not involved in the presented research. Participants rated themselves as highly experienced with computers and mobile phones (scale used: 1=none, 2=poor, 3=medium, 4=high, 5=expert). Only 4 out of 12 indicated a high experience with car navigation systems.

All of them had experience with pedestrian navigation in terms of using paper maps or tourist guides and half of them had used electronic devices for pedestrian navigation before. Two participants had never been to the area of the study before, three had been there a few times, and the others had been living there for some time. However, since the routes were not shown on a map and participants did not know their destination, but only received instructions on where to travel before they actually had to turn, there was no advantage in being familiar with the area.

Experimental Design

The experiment used a within-subjects design with one independent variable: navigation technique, with three levels: *NaviRadar*, *PocketNavigator* and *Spoken Instructions*. Three different routes were selected in an area within the campus of Lancaster University which is occupied by many 5-floor student houses. Within a small area, it offers a high number of crossings (see Figure 11).

Figure 11. Routes I-III on Lancaster University campus.

Table 4 shows the number of left and right turns per route, the number of crossings where the participants had to go straight on, and the overall length of the routes. The participants experienced the three different navigation techniques in counterbalanced sequences using a 3x3 Latin square and all of them experienced the routes in the sequence I → II → III. Using this approach, every navigation technique was used four times per route.

Route	Left turns	Right turns	Overall turns (+ crossings without turns)	Overall length
I	6	4	10 (+5)	360 m
II	5	5	10 (+4)	410 m
II	6	4	10 (+3)	370 m

Table 4. Characteristics of tested routes.

Procedure

Participants took part in the study individually. In the beginning, they were introduced in the purpose of the study. The researcher then led them to the starting point of the first route. There, they were introduced into the first navigation technique. In the case of the spoken instructions, they were presented with some sample instructions. For the tactile approaches, a more sophisticated training was needed. Here, the concept was explained to the participants and then 18 directions were presented (similar to the first study, see Figure 5f) where they had to indicate where they would travel using a circle on the phone. Participants were allowed to ask questions throughout the experiment. The next stage was to instruct the participants to navigate the first route using the given navigation system. They were instructed to walk with their normal walking speed while two experimenters accompanied them. One experimenter was responsible for the user's safety, answered questions if needed, and led the user back to the route if they walked in the incorrect direction for more than 5 meters. The other experimenter filmed the study. After each route, participants were asked to answer questions about their subjective impression of the most recently tested navigation technique and could provide additional comments. After all three routes had been completed, a further questionnaire was filled in that contained questions about participant demographics, as well as a comparison and ranking of all three systems.

Limitations of the Study

An important issue during the user study was the inaccuracy of GPS measurements which have been negatively influenced by the proximity of nearby buildings. Several tests had been run before the study to decide on the best placement of waypoints so that instructions are provided at the correct time. Unfortunately, traces from the tests are widely spread around the defined route. This led to problems with the timing of commands and even incorrect indications. Incorrect indications were logged during walking and by analyzing the videos taken during the study, the behavior of the participants at these turns are not included in the following count of errors or disorientations. 26 out of 120 crossings have been removed for NaviRadar, 27 for PocketNavigator and 13 for spoken instructions. Another problem was the compasses used (external for the NaviRadar and internal for PocketNavigator). They were calibrated between the tests, however, measurements showed incorrect results on three occasions. When this occurred, the compasses required recalibration. Moreover, task completion times were not examined since these are distorted by GPS/compasses issues and environment obstacles, such as passing cars. It was anyway not expected that the task completion time between the three navigation techniques varies significantly as the most important contributing factor is the time needed for walking and the time needed for navigation is almost negligible as already shown in [15].

Results

The study results show that all three navigation techniques could be effectively used for navigation. Figure 12 shows the overall number of disorientation events and navigation errors that were observed during the study. An error occurred when a participant travelled in the incorrect direction for more than 5 meters. When this occurred, the participant was stopped by the experimenter and was redirected back to the correct route. A disorientation event was recorded when the participant stopped for more than 2 seconds.

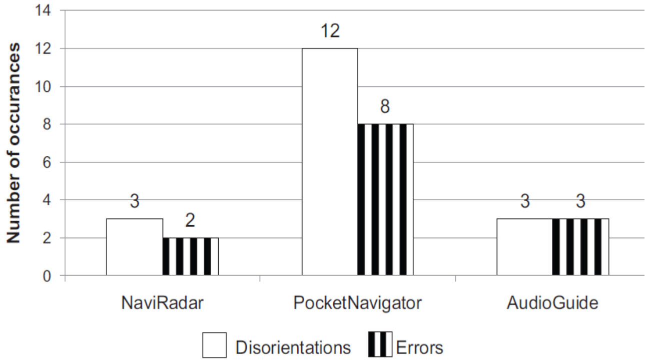


Figure 12. Overall count of errors and disorientation events for all participants.

NaviRadar and spoken instructions both had a very low number of errors (only 3 times each for all participants). Participants using PocketNavigator travelled in the incorrect direction 8 times. When using NaviRadar and PocketNavigator, the errors occurred when a signal was misunderstood, while errors with the spoken instructions occurred when several turns to one side were available and participants took the incorrect one because they misjudged the provided distance, for instance, they turned left after 25 meters when the instruction "In 45 meters, turn left" had been given. Disorientation events occurred four times more often, overall at 13% of crossings, when using the PocketNavigator when compared with the other two systems (both 3%) and additionally participants estimated their walking speed slower when compared to the other two. This is due to the concept that a new direction is only shown when the last waypoint had been reached. Participants slowed down when coming to a turn waiting for the new direction to be indicated or stopped walking for scanning the new direction.

Perceived usability satisfaction of the three navigation techniques was measured using the IBM Computer Usability Satisfaction questionnaire; this showed positive results for all three approaches. Spoken instructions had the highest average usability satisfaction followed by NaviRadar and PocketNavigator. No significant differences in the ratings of NaviRadar and spoken instructions could be detected. This suggests that our tactile interface did not affect the ratings negatively compared to the (commonly used) audio feedback. In contrast, PocketNavigator was rated significantly worse than spoken instructions in terms of ease of use, learnability, completion time and satisfaction level ($p < .05$). An analysis of the perceived task load using the NASA Task Load Index showed a low to very low task load for spoken instructions and a neutral to low task load for the other approaches. In terms of mental demand and effort, the advantage of spoken instructions is statistically significant ($p < .05$). However, there is no significant difference regarding the frustration level of NaviRadar and spoken instructions. This indicates that even raised effort (at least in the beginning) in order to understand the tactile feedback does not affect experienced frustration. Furthermore, we asked the participants to state their first, second and third preference towards the three navigation techniques. Spoken instructions received on average place 1.33, NaviRadar 2.25 and PocketNavigator 2.42.

CONCLUSION

This paper introduced NaviRadar, a novel approach for pedestrian navigation that uses a single vibrator and distinct tactile patterns to communicate the distance to the next crossing (where the user has to turn) and the direction in which to travel. The first study was conducted in the laboratory and showed the feasibility of the NaviRadar concept as the participants were able to identify communicated directions with a mean deviation of 37°. The second study showed that NaviRadar worked in a realistic outdoor setting. What's more, it had a similar performance regarding usability and errors when compared with spoken instructions (with which most participants were very familiar with) and performed better – especially in terms of errors and disorientation events – when compared with the PocketNavigator approach.

In our future work, we will evaluate the effect of a shorter circulation time of the radar sweep from which we expect a higher accuracy in terms of the perceived direction. Furthermore, we will investigate approaches to handle incorrect GPS and compass readings through more sophisticated filtering algorithms. Moreover, we plan to test how the directional accuracy improves through prolonged usage of NaviRadar and how NaviRadar could efficiently be added as a feature to current solutions such as Ovi or Google maps.

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