Tactile Wayfinder: A Non-Visual Support System for Wayfinding

Wilko Heuten[1], Niels Henze[1], Susanne Boll[2], Martin Pielot[1]

[1]OFFIS
Escherweg 2
26121 Oldenburg, Germany
{heuten|henze|pielot}@offis.de

[2]University of Oldenburg
Escherweg 2
26121 Oldenburg, Germany
susanne.boll@uni-oldenburg.de

ABSTRACT

Digital maps and route descriptions on a PDA have become very popular for navigation, not the least with the advent of the iPhone and its Google Maps application. A visual support for wayfinding, however, is not reasonable or even possible all the time. A pedestrian must pay attention to traffic on the street, a hiker should concentrate on the narrow trail, and a blind person relies on other modalities to find her way. To overcome these limitations, we developed a non-visual support for wayfinding that guides and keeps a mobile user en route by a tactile display. We designed a belt with vibrators that indicates directions and deviations from the path in an accurate and unobtrusive way. Our first user evaluation showed that on an open field without any landmarks the participants stayed well to given test routes and that wayfinding support is possible with our Tactile Wayfinder.

Categories and Subject Descriptors

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

General Terms

Tactile Display, Pedestrian Navigation, Wayfinding, Human Factors, Experimentation

1. INTRODUCTION

Maps and route descriptions are well established means for wayfinding. In large cities such as Rome or Berlin, you will often see visitors that aim to find their way to a sightseeing spot or to their hotel, using a paper map. Also hikers often use a map to follow the trail and to decide at crossings where to go. In recent years, also digital mobile support has reached the end consumer. Mobile applications allow to access city maps and display route descriptions. The iPhone now brought Google maps on a nice display to the traveler. Special outdoor devices help the hiker and mountain biker to stay on their trail over hill and dale. These systems, however, rely on the visual sense and visual attention, which is at the same time needed by the pedestrian for the walking task. Hence, these systems drag part of the attention to the display, forcing the walker, hiker, biker to stop and focus on the device or reduce their attention on their surroundings, which may be risky. Another option could be to also use speech instructions for pedestrian navigation. This however may be far to intrusive. Using small speakers, the persons would then be surrounded by sound, which might annoy others. Employing head phones is not an option too, as the auditory sphere is a very helpful feedback for a safe journey, not only for blind persons. The acoustics around us indicate that a car is approaching from the left and we should stop at the walk way, or give us hints that the ground under the mountain bike becomes smooth and we may lower our speed etc. To conclude the traditional wayfinding support systems that we find today rely on the visual and the auditory sense may not be the best choice for supporting a mobile user.

Therefore, we developed the Tactile Wayfinder, a portable user interface, which can be attached to existing navigation system solutions for pedestrians, but takes the mobile situation of a user into account in which the visual sense is needed for concentrating on traffic, the surroundings, the track, or is not available. In contrast to visual maps or speech navigation systems, the Tactile Wayfinder provides route information non-visually and non-intrusively. The main part of the system is a tactile display, which is worn as a belt. A specific process facilitates a homogeneous and an accurate presentation of direction information, guides the user to the destination and mediates orientation.

In the following, we present the design and the evaluation of the Tactile Wayfinder. In Section 2, we introduce the reader into wayfinding and the field of spatial cognition. Looking more closely into the task of wayfinding, we elaborate the user situation for the Tactile Wayinder in Section 3. In Section 4, we present related work in the field of mobile navigation systems and multimodal mobile systems. The design of the Tactile Wayfinder and how it supports the tasks of wayfinding in described in Section 5, followed by an overview of the system design and implementation in Section 6. We have carried out a first evaluation of the tactile display on an open ground. We present the evaluation method and the observations of the evaluation in Section 7. The paper concludes with a conclusion and outlook to future work.

2. WAYFINDING

Many disciplines like history, cartography, geography, urban and regional planning, cognitive science, computer science, biology, astrology, and medicine deal with the cognitive processes of traveling. They often have a different association with the term *wayfinding*, which likely leads to confusion in interdisciplinary communications. In this section wayfinding and its cognitive requirements are examined, to understand what tasks and information are involved and need to be considered in the design of a wayfinding support. Several researchers have discussed the term wayfinding already and proposed different definitions. They all, however, have in common that the major challenge of wayfinding can be found in the cognitive activities. For the progression of this work we use the definition and process description from the geographer Downs and psychologist Stea, as this provides us with the most information about the user tasks need to be investigated for the presentation design. They define wayfinding as:

> "the process of solving one class of spatial problems, the movement of a person from one location on the earth's surface to another."[3]

They divide the process of wayfinding in four tasks: Orienting oneself in the environment, choosing the route, keeping on track, and recognizing that the destination has been reached, which are illustrated next:

2.1 Wayfinding Steps

The first step in wayfinding is orientation, which leads to knowledge where people are in relation to some other places. This requires knowledge about the other places, beforehand. The acquisition of it is according to Downs and Stea not part of wayfinding. Orientating in the environment leads to the knowledge, where one is located and how one is oriented in relation to the environment. In literature this is also known as the *sense of direction.*

The second step, the choice of the route, requires that a person makes a cognitive connection between the current location and the desired destination. A correct route should connect a starting point, for example, the current location of the traveler, with the destination. In an urban environment there is often no direct way to reach a destination without any turns. Obstacles like buildings, private properties or natural objects like rivers, hinder the navigator. Path networks provide the basis for moving around in urban environments, except for some special features like large places. Usually there is more than one possible correct route to get to a destination. The choice, which route to take, depends on a consideration of many individual and external factors, for example, the distance of the routes, the constitution of the paths, safeness, simplicity, or the points of interests along the route. The choice can also take place before traveling (cf. [14]), which usually leads to route instructions, an external representation of decision points and directions.

The third step, keeping on the right track, refers to the monitoring of the route and ensures during the movement that people are still on the chosen way. This includes that the traveler makes the right decisions at the decision points. During this activity the traveler constantly orientates oneself in the environment and maps the current location onto the cognitive map. Landmarks play an important role in this activity. They are observed by the navigator permanently. Any rotation or movement results in the perception of landmarks from different perspectives, being an evidence of locomotion towards or away from the destination and confirming that the traveler is still on the chosen route. In addition, the navigator performs adjustments to keep track on the current path, like the sidewalk, avoiding obstacles, and returning to the route.

The fourth step of wayfinding, recognizing the destination, completes the wayfinding process. In order to perform these steps, people need to understand the environment.

2.2 Spatial Cognition

Spatial cognition deals with how the environment, which is perceived through our senses, is represented in the human's brain and how this representation is accessed and used for reasoning. Many works have been done to explain the spatial cognition. These resulted for example in the description of *cognitive maps* (c.f. [3, 5]) or *cognitive collages* [16]. The content of a cognitive map of an environment can be distinguished in *route* and *survey knowledge* [8]. Later literature distinguishes between *route, survey,* and *landmark knowledge*, for example [10]. The simplest form of route knowledge consists of a series of connections between points. Connections are paths, like streets, sidewalks, and tracks, or imaginary ones like ways on water or on large squares. Prestopnik and Roskos-Ewoldsen describe survey knowledge abstractly as the integration of places and the relations between them. It has a global focus and relies on more universal concepts that do not change, if the direction or orientation changes [12]. The knowledge about landmarks contributes to the traveler's orientation and localization within a spatial environment. They help us organize our spatial knowledge and to anchor actions, while following a route [5] and help to make decisions, confirm that the navigator is still on track, and to improve route knowledge.

The different types of knowledge have advantages and disadvantages regarding to wayfinding, and in particular for following a route. Landmark knowledge alone is usually insufficient for choosing or following a route, but is useful for orientation and localization in a spatial environment. Route knowledge exists in egocentric perspective, which relies on the traveler's location and orientation. It is therefore unidirectional: Knowing a route from a place A to a place B, does not lead directly to knowledge of a route from place B to place A, as the sequence of connections and decision points must be reversed and the direction of them to not match anymore. Additionally, when leaving the route, the traveler likely gets lost and might not find back to it. On the other hand, from the cognitive point of view the egocentric perspective is very efficient. When following the route, the information about directions can be accessed and used directly without any transformation. Survey knowledge exists in an allocentric or global frame of reference. It is therefore much more flexible compared to route or landmark knowledge. The traveler can find shortcuts and bypasses as well as estimate distances and directions. From the cognitive load perspective, however, in order to follow a route, directions have to be transformed from the global perspective to the egocentric perspective. This results in a higher cognitive effort for the traveler.

In this section we have investigated the foundations for wayfinding. Its terminology, different tasks, and important cognitive aspects relevant for a system aiming at wayfinding support have been proposed. In the following section the user situation is being analyzed.

3. SITUATIONAL CONTEXT

The steps during wayfinding which have been discussed above implicate the functional requirements for a wayfinding system. This section analyzes the situational context of pedestrians, hikers and bicycle riders to elicit the non-functional requirements for wayfinding applications targeted at the respective user group. Each discussed requirement is assigned a number for later reference.

Traditional maps and above mentioned GPS applications need the visual attention of the user, if he or she wants to navigate. For the most part, the visual sense is needed by the pedestrian, hiker or bicycle rider for their walking or driving task. The more hazards like traffic, other people or obstacles exist, the more these users have to focus their visual attention on their surrounding instead of a visual map (Req.1).

For using traditional maps as well as the above mentioned Google maps users need to hold the artifact in the hands if he or she wants to orientate him- or herself. While walking this might work if the user does not have to carry other things like luggage, shopping bags or an umbrella to protect him- or herself from the rain. Although riding with one or no hand is possible, it is very unsafe in critical situations. Hikers might face impassable terrain where they had to use the hands to keep their balance, protect themselves from branches, or climb over obstacles. Thus, in many possible scenarios it would be helpful if the wayfinding solution works hands-free (Req.2).

For keeping eyes and hands free, auditory feedback is an option, which is like visual feedback well-established in existing car navigation systems. The difference of using sound in a car or using sound when riding, walking or hiking is that cars offer a controlled environment in form of a sound-proof interior. Under open sky conditions speakers might not be heard or annoying people, while headphones would be leaving the users without their auditory channel which is important for hazard detection outside their field of view. Thus, the system should not use auditory feedback mainly (Req.3).

Considering the users safety, all applications based on auditory and visual feedback could only be used when users stop in a safe location. While continuous feedback is wanted, it has to be considered that wayfinding solutions might be carried for many hours, so the system should minimize stress when using it. Thus the feedback has to be intuitive, easy to understand while being unobtrusive at the same time (Req.4).

Some people are fascinated by the latest technical devices using and carrying them as status symbol. Anyway, solutions that require wearing or carrying expensive, awkward technical equipment that is visible to others might prevent many people from using the system in public. Thus the technical equipment should either be well accepted technical equipment like mobile phones or be ubiquitous and invisible to other people (Req.5).

4. RELATED WORK

Today, most commercial Wayfinding systems are targeted at automotive use. These systems use visual and auditory output for guiding the user along the street network. Nowadays these applications can also be found on mobile devices equipped with a GPS receiver, which can also be used in other contexts such as hiking or riding. However, since the interaction is mostly similar to established car navigation systems, they do not explicitly address the special requirements of pedestrians or cyclists. Existing wayfinding systems that are targeted at pedestrians can be structured by their main interaction modality.

Similar to the above-mentioned wayfinding systems are interactive maps. Systems like Cyberguide [9] or LoL@ [11] display the user's position on an interactive map allowing him or her to orientate in an unfamiliar environment. Other approaches combine photos of prominent landmarks with navigation directions. These systems have in common that they require the user to carry the display in his or her hand. Other systems [2] address this issue by making use of head-mounted-displays to free the user's hands. Still all mobile applications relying on visual displays share the same problems. Displays require the user's attention while interpreting the visual presentation. This requires the user to interrupt critical tasks like walking though a crowded environment or riding a bike when interacting with these user interfaces. Naturally, interfaces based on visual output also exclude people with visual impairments.

The use of sound for guidance has been explored by several people. Trekker [7] is a commercial wayfinding aid designed to be accessible for visually impaired that relies on speech in- and output. However, speech requires the user to concentrate on the auditory output to not miss important information and tends to be distracting. Transcribing spoken directions into the real world requires the user's interpretation, which produces stress and is likely to be error-prone. Since speech presents information only serially, it leaves the human ability to process multiple auditory stimuli in parallel and subconscious unused. AudioGPS [6] exploits this potential by presenting information in an ambient always present manner. It continuously displays a spatial non-speech sound which shows the direction of the destination, e.g. next waypoint. Auditory systems share the problem that an important sense is being occupied limiting the primary perception of the environment to the field of view.

Tactile displays are a solution to this issue, since they do neither block the visual nor the auditory sense. There are hand-held systems like haptic gloves [17] applying tactile displays for guiding the user along the route. The Rotating Compass [13] combines the vibrotactile display of a mobile phone with a visual compass. Whenever the correct direction is shown, the phone vibrates, which frees the user's hand. ActiveBelt developed by Tsukada and Yasumura [15] is a belt-type tactile display consisting of eight vibrators that are equally distributed around the user's torso. The FeelNavi application combines the ActiveBelt with a navigation system. The user's destination is displayed by activating the vibrator most closely pointing into the destination's direction. This limits the number of directions that can be expressed to the discrete number of vibrators, resulting in very inaccurate directions. Van Erp [4] et. al. evaluated a similar belt for guiding pedestrians along a route consisting of several waypoints. The evaluation showed promising results for hands-free guidance, but the discrete number of displayable directions caused the users not to take the straight route towards the subsequent waypoint in some cases. In comparison to existing solutions, we aim to provide the user with a continuous tactile display, which allows to provide more accurate and more non-intrusive direction presentation. With this it becomes feasible to mediate directions of a curved path, which should be followed in contrast to existing solutions, which mediate strong direction deviations, e.g. at crossings only.

Existing applications for wayfinding do not consider the situational context of pedestrians, hikers and bicycle riders as we discussed in Section 3 adequately enough. In the following, we discuss the design of a wayfinder aid to satisfy these non-functional requirements.

5. TACTILE WAYFINDER DESIGN

Resuming the wayfinding steps discussed in Section 2.1 that need to be performed to successfully reach a destination, there is some potential for electronic systems to support the traveler. The first step, which leads to a location in the environment can be carried out by using localization techniques such as the Global Positioning System (GPS). The second step, choosing the route, can be performed by an electronic system with knowledge of the origin, destination, and the underlying path network (map data). The wayfinding aid takes over the acquisition of route and survey knowledge, so that the traveler does not have to take care about this. The most challenging step is to keep the user on a given route. Here, the specific mobile user situation as investigated in Section 3 has to be taken into account, when designing the interaction. To overcome this challenge we developed the Tactile Wayfinder, which consists of a spatial display to keep and guide the user on the planned track by mediating information through pressure on the skin. For this, two tasks need to be solved: First, the display conveying the necessary information to the user has to be developed, as available displays are not suitable. Secondly, the usage of this display during the wayfinding process of the traveler needs to be designed.

5.1 Designing a Spatial Tactile Display for Wayfinding

In order to keep the traveler on the route, the most important and most frequently needed information is the direction the traveler needs to go. In the following, it is shown, how the display is designed and worn by the traveler. Afterwards, the concept of presenting direction information accurately and non-intrusively through this display is described.

5.1.1 Wearing the Tactile Display

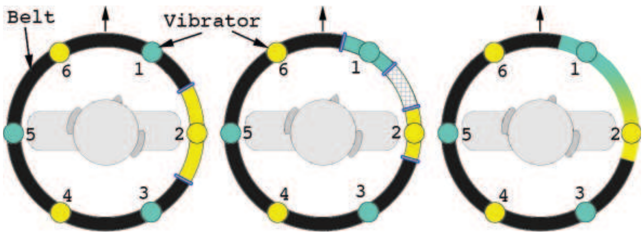
The humans' skin consists of sensors, which can be stimulated by touch or vibration. These sensors are spatially distributed over the skin surface. People are able to perceive stimulation changes fast and accurately and can localize, where they occur. The Tactile Wayfinder makes use of this biological property. Tactile signal transducers are attached externally to the body and form a spatial display. Information like directions provided through this is perceived very quickly and efficiently without burden the visual or auditory channels (Req. 1 and Req. 3). Tactile stimuli are sensed directly, which means that they do not have to be encoded in specific patterns or instructions. Direction information is interpreted easily by the user, which minimizes the stress and is easy to learn (Req. 4). Additionally, it is provided in an egocentric perspective, taking the user's current orientation into account, to keep the cognitive load low compared to an allocentric presentation (c.f. Section 2.2).

For the wayfinding tasks, direction information around the vertical axis is sufficient. Therefore, the tactile transducers are distributed onto one level around the vertical axis of the body. Not all body parts are equally equipped with sensors and are not equally sensitive. Additionally, not all regions are adequate or convenient to carry a tactile display. With a first prototype consisting of one SGH 400 vibration motor from a mobile phone we tested in a user study, how the tactile stimulation is perceived on nine different body parts. We also asked the participants to rate the comfort and attractiveness to wear the vibrator on the respective position. It was found out that for the male participants the breast and the hip scored best. The two female participants stated that wearing the tactile signal transducers at the breast was uncomfortable, but also liked the hips as the most promising area to attach the vibrators. From this study we concluded that a tactile display worn as a belt is most promising regarding the acceptance and perception. With this, it is easy to carry and keeps the hands free for other tasks (Req. 2). A belt itself is already being used by many people as a garment and does not represent a foreign object. Additionally a belt can be worn without attracting the attention of other people (Req. 5).

5.1.2 A Non-Intrusive Continuous and Accurate Direction Presentation

There are no spatial tactile signal transducers available, which cover a two-dimensional region and could be used directly for the belt. Therefore, multiple single tactile signal transducers are used to create the spatial display. These are evenly distributed over the belt, so that the whole spatial range is covered (see Figure 1). One signal transducer covers a certain range of directions, depending on the total amount of transducers. The number is influenced by several factors, such as the size, the length of the belt, the flexibility, and the power consumption. It is always a compromise between these factors and the direction accuracy. Following van Erp [4] et. al., from a tactile perception point of view, a resolution of about 10° in the horizontal plane is feasible, which would result in 36 signal transducer for an optimal tactile display, which covers 360°. However, the less transducers are used for the display, the better fits the belt on the body. An objective for the belt production is to use as few transducers as needed. For the ones used in this work, six vibrators were determined as an ideal solution. This allows technically a precision of 60°. Figure 1 (a) illustrates that Vibrator 2 is responsible for displaying directions between 45° and 135°, as indicated by the highlighted area.

This concept reveals two implications regarding the aim of an accurate and non-obtrusive wayfinding support. First, a range of 60° is not accurate enough to present slight deviations from the path. Secondly, the continuous rotations of the traveler can only be presented step by step, due to the reliance on a discrete number of signal transducers. This is on the one hand obtrusive and becomes annoying, and on the other hand, no immediate and synchronized feedback for the rotation is given. A rotation within the coverage of one vibrator does not provide any signal changes. In order to increase the accuracy, we activate two adjacent vibrators at the same time for a direction presentation between them. This is illustrated in Figure 1 (b). Directions belonging to the patterned area between Vibrators 1 and 2 are presented by activating both ones. With this, the coverage is reduced of each single transducer to a half. This method allows technically to raise the accuracy to 30° when using six vibrators and reduces the coverage for a single vibrator. However, rotations can still not be presented in a continuous way. Based on this solution, we further improved the design: The Tactile Wayfinder takes advantage of the ability to apply different intensities to the tactile transducers, allowing continuous stimulations. The transducers are interconnected and directions are displayed by interpolating the intensities of two adjacent ones. Figure 1 (c) illustrates this concept for Vibrator 1 and 2. A direction of 30° is presented with an intensity of 100% for Vibrator 1, while Vibrator 2 is switched off, which means a strength of 0%. If the direction turns continuously to 90°, the intensity is reduced for Vibrator 1 and increased for Vibrator 2 accordingly. At 60° both have a strength of 50%.



(a) (b) (c)

Figure 1: Design steps towards an accurate and non-obtrusive direction presentation. (a) One vibrator is used for direction presentation. (b) Two adjacent vibrators are activated simultaneously for the presentation of a direction in between. (c) Final design: Interpolation over the intensities of two adjacent vibrators is applied and allows a smooth, continuous, and accurate presentation

Through the interpolation the traveler perceives directions and their changes homogeneously and continuously. Intensities are adjusted equivalently to the traveler's rotations and provide immediate feedback: Slight deviations from the path lead to slight intensity adjustments, sharper deviations lead to higher changes.

5.2 Designing Presentation and Interaction for Wayfinding

During wayfinding, the traveler is exposed to a high cognitive load. The interaction and presentation must therefore carefully be designed and additional interruptions of the primary user tasks, such as avoiding other travelers and obstacles, should be omitted. Explicit communication with the wayfinder aid must be kept as low as possible. In the following, it is described how the Tactile Wayfinder takes these considerations into account.

While moving from a location A to a destination B, two possible causes lead to a deviation from the path, so that the traveler is not on track anymore. First, the path changes its direction, either on a segment or at a decision point or, secondly, the user changes its orientation. For the Tactile Wayfinder it does not make any difference to the presentation, which one occurs. The calculated deviation between the user's orientation and the path direction is displayed to the user via the belt. Tactile stimuli convey the deviation from the path and indicate the direction to get back on track. Figure 2 illustrates an example. In the first step, the traveler is on the track. The belt vibrates in the front. From Step 2 on the traveler deviates from the path and the tactile stimulation moves continuously to the right from the perspective of the traveler. In Step 4 the traveler begins to turn in the direction of the route and the vibration wanders back to the center, until the traveler is back on the track again as indicated in Step 5.

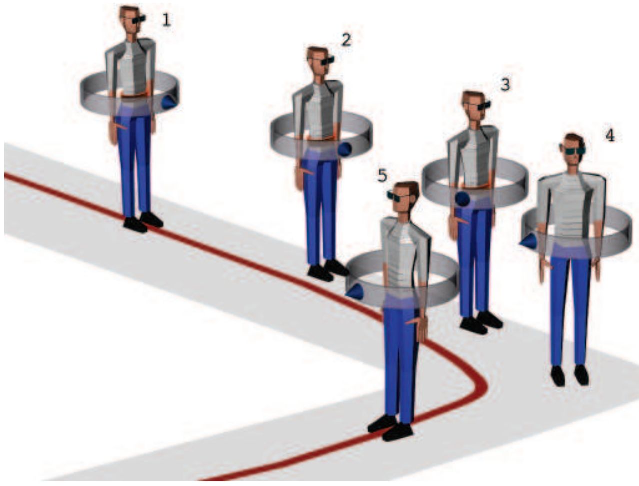


Figure 2: Route guidance by the Tactile Wayfinder. The cone marks the position of the tactile stimulation

From this point of view, a three-way relationship forms the interaction: the user, who change the orientation and location, the environment through the progression of the path, and the Tactile Wayfinder that conveys information to the user depending on both, the user and the environment. Although the interaction takes place permanently, it is performed implicitly while walking through the environment. There is no need for the user to interact explicitly through the wayfinding process, unless any changes of the route are necessary. Our solution contains only essential functions, is therefore simple to operate, minimizes stress during wayfinding, and is easy to learn.

The Tactile Wayfinder as designed in this section supports the traveler in keeping her on the route. The cognitive load, the specific user requirements in a mobile situation, and the necessary information to perform this wayfinding task are considered in the presentation and interaction design. In the following, the development and implementation of our demonstrator is proposed.

6. SYSTEM DESIGN AND IMPLEMENTATION

The main part of the Tactile Wayfinder is the tactile display, which is worn as a belt around the hip as shown in Figure 3. The Tactile Wayfinder consists of two hardware components, which communicate wireless via Bluetooth or

Figure 3: Wearing the Tactile Wayfinder

alternatively through a standard serial cable with each other: a Personal Digital Assistant (PDA) and the tactile display, consisting of the belt and the container for the electronics (see Figure 4). The belt and the container are firmly joined through electric cables, which connect the electronics with the signal transducers.

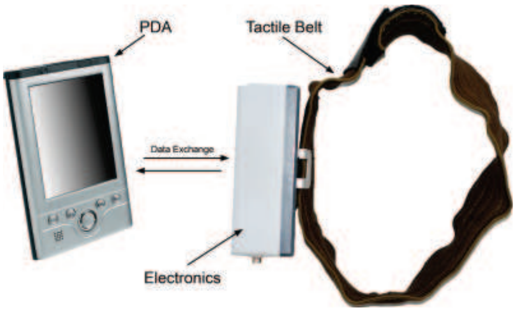


Figure 4: Tactile Wayfinder Components

On the PDA runs a wayfinder application, which manages the access to the geographic map data and route information. It determines the position of the user via the Global Positioning System (GPS). At the user's location the direction of the path is calculated, which is related to north (0°). The path's direction is sent to the tactile display. To facilitate the communication between PDA and tactile display an application programming interface (API) was developed in standard C programming language and built as a native Dynamic Link Library (DLL). It runs on Windows Mobile 2003 and 2005.

The tactile display consists of the tactile belt as well as the respective electronics, which are necessary to control the tactile transducers in the belt. The two main electronics components are a digital compass and a microcontroller. The digital compass measures the absolute orientation of the user, from north. It has to be mounted horizontally to provide reliable values. The microcontroller contains the software, which performs direction calculations, controls the intensity of the vibrators according to the design described in Section 5, and exchanges information with the wayfinder application on the PDA. It requests periodically the compass value, which is then used together with the direction of the path sent by the wayfinder application to determine the new direction relative to the current user's orientation. The system is currently supplied by standard 9V batteries.

The tactile belt consists of a flexible tube out of fabrics, which can be worn with a hip extent from approximately 60 to 80 cm. The vibration motors are sewed into the tube. The cables to supply the signal transducers with electricity are integrated into the tube. The user's skin does not have direct contact with the vibrators or cables. For the current prototype six vibration motors from mobile cellular phones are used. These are composed of an unbalanced mass on a rotating axis and can produce vibrations of high frequencies. Additionally, they are produced in high quantities, which decrease their costs, and are made for the mobile and outdoor usage. They are small and light-weighted, provide the necessary range of frequencies, and have a low inertia. Samsung SGH A400 and Samsung SGH A600 motors have been compared (see Figure 5). Because the SGH A400 has a slight advantage due to its lower power consumption, this one is used for the tactile belt. To improve the perception of the stimulation, it was attached onto a small plastic plate, which acts as an amplifier.

Figure 5: Samsung A600 (left) and Samsung A400 vibration motors (right)

The system design and implementation facilitate testing and evaluation of the Tactile Wayfinder concepts.

7. EVALUATION

We conducted two evaluations. Our objective was observing the system as a whole to investigate how the it should be further developed and what should be subject to future experiments. In the first evaluation we examined the accuracy of the directions perceived by users in a controlled environment. In the second evaluation we took the belt outside to investigate, how well it serves as a wayfinding aid. For each evaluation procedure, observations and discussion are presented in the following.

7.1 Direction Accuracy Perception

In the first evaluation the tactile belt, as developed in Section 6, was used to find out how accurate the presentation of the spatial display can be perceived by participants. The presentation of directions followed the design concept described in Section 5.1.2.

7.1.1 Evaluation Procedure

Nine male and four female participants in the age of 28 to 70 years without any noticable disability conducted the evaluation. None of them had any experiences with tactile user interfaces. Before the experiment started, the objective and the functionality of the tactile belt was explained. After putting on the belt, the assistant assured that the users aligned it correctly, so that 0° was in front. The evaluation was performed without any training. 22 different randomly selected directions were displayed after each other. All participants obtained the same directions in the same order. After presenting each direction without time restriction, the participant was asked to indicate the felt angle using a compass rose with a rotating needle. Directions were marked with angles every ten degree on the compass.

7.1.2 *Observations*

The average mean deviations for each participant of all displayed directions are shown in Figure 6. The smallest average deviation was 12° for Participant 8 and the largest was 38° for participant 1. The total median deviation over all participants was 15° and the average deviation was 15°. Figure 7 illustrates the mean deviation for each tested direction. The figure shows that the minimum mean deviation (6°) was measured for 0°. The maximum was determined for 77° with a mean deviation of 31°.

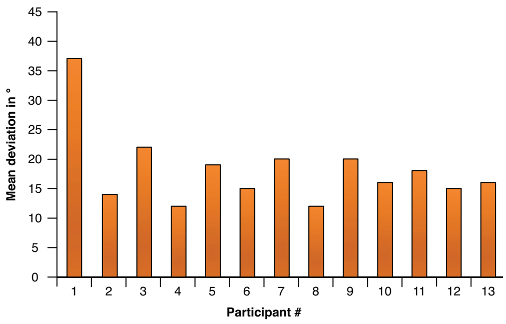


Figure 6: Mean deviation for each participant over all displayed directions

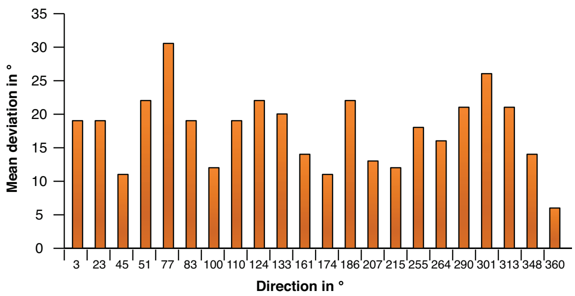
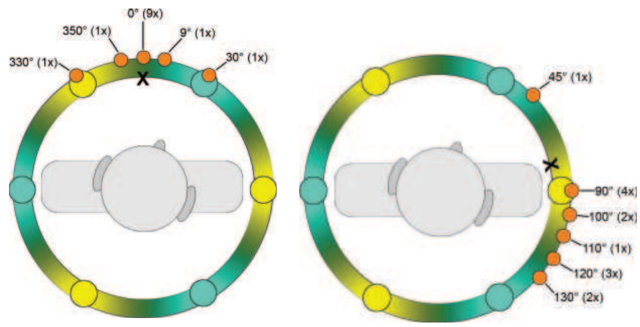


Figure 7: Mean deviation for each displayed direction over all participants

These extreme cases are visualized in Figure 8. For the 0° angle nine participants perceived the direction exactly, two participants had a deviation of less than 10°, and two participants rated the direction at one the closest signal transducers with a deviation of 30°. The 77° direction was rated quite inaccurately, the closest answer was 90°which was given by 4 participants.

7.1.3 *Discussion*

The evaluation showed that participants were able to express displayed directions with a deviation median of 15°. Causes for this deviation and ways to further reduce it will be discussed in the following. First, it seemed difficult for the participants to give feedback about the perceived direction that was displayed by the tactile belt. It was challenging for them to transfer the sensed vibrations on the skin to the compass rose, which was used to measure any difference of the presented and perceived direction. It is assumed that this logging method introduces errors. In addition, most participants tended to rate cardinal numbers, such as 45°, 90°, or at least angles in 5° or 10 textdegree steps. The feedback is not necessarily coherent to the perceived direction, but rather a simplification of the participants. For future evaluations the method to record the participant's feedback should be reconsidered.



(a) (b)

Figure 8: (a) Directions perceived by the participants for the 0° angle, (b) Directions perceived by the participants for the 77°angle

A second reason results from the human perception. For some directions, such as 77°, a higher deviation was observed than for others. One reason is that humans are not equally sensitive for tactile stimulation at different parts of the body and perception might be different between individuals. To reduce the deviation a general adjustment of the signal transducers could be implemented. Some transducers, for example, would operate with higher intensities, or for certain body parts different types with different size or pressure, could be used. In addition, an individual calibration could improve the uniform perception. During the calibration process, signal transducers would be assigned with different intensity ranges. For some participants it was observed that they got better during the experiments. The time of wearing and feeling the belt might have influence on the perception. A training program could improve the direction perception.

A median deviation of 15° between a perceived and a presented direction is better than what currently available systems can provide non-visually, which use mainly verbal instructions or inappropriate spatial sound. The observations indicate that the perception in the front is accurate. That is particularly important for route guidance, as deviations from the path will presented in the front area first.

7.2 Wayfinding Support

After determining how accurate directions can be perceived by users without moving in a well-defined environment we evaluated how the system performs outside the lab in a navigation task. The question we answer with this evaluation is if the system can be used to guide along predefined routes. We analyzed the deviation of users' paths from the route and the required time to complete. The non-comparative evaluation is described in the following.

7.2.1 Evaluation Procedure

To conduct the evaluation the application developed in Section 6 was used. The PDA application manages the routes and receives the user's position via a GPS receiver. The presentation follows the egocentric design concept described in Section 5.2. The system's output consisted solely of the direction of the route's next waypoint displayed via vibration.

The evaluation was conducted on a 150m wide and 150m high meadow without any tracks or landmarks. To evaluate routes with sharp turning points as well as large curves two routes were defined. The first route shown in Figure 9 consists of four sharp turning points and is 375 meter long.

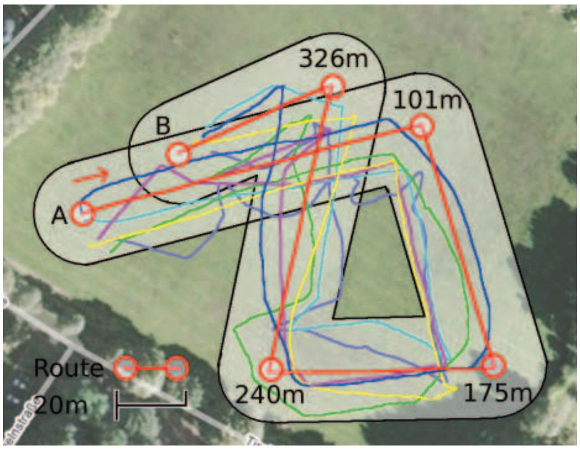


Figure 9: The first route from point A to point B and the tracks walked by the participants. A 15m corridor around the route is highlighted.

The second route in Figure 10 consists of large curves and is 430m meter long. Technically the routes consist of connected waypoints that must be reached by the user. The application displays the direction of the next waypoint with the tactile belt. A waypoint is reached and the next waypoint displayed, if the user is closer than 15 meters to the active waypoint. The threshold of 15 meters was chosen to compensate the inaccurate GPS localisation and ensure a smooth presentation. A new position was obtained by the GPS receiver every second. The user's orientation updates the output with approximately 25 Hertz. The system recorded every second the user's position and orientation.

Participants were picked up aside the meadow. After a brief introduction to the belt and the evaluation procedure the belt was attached to the participant's hip. The tactile feedback started showing the direction of the first route's starting point. The participants were asked to maintain normal walking speed. The participants were guided to the corner of the meadow, then they followed the vibration along the route till they reached the starting point of the second route. There, the vibration stopped and the assistant started the second route. Meanwhile an assistant followed the participant in short distance to answer questions and assist the participants. After finishing the second route questionnaires concerning the device's comfort and performance were handed out to the participants.

Three woman and four men between 24 and 40 years old participated in the evaluation. All participants had no mentionable mental or physical impairment and similar waist sizes. None of the participated in the previous evaluation or had special experience with tactile interfaces for navigation. They neither had pre-knowledge about the routes nor saw other participants performing the evaluation.

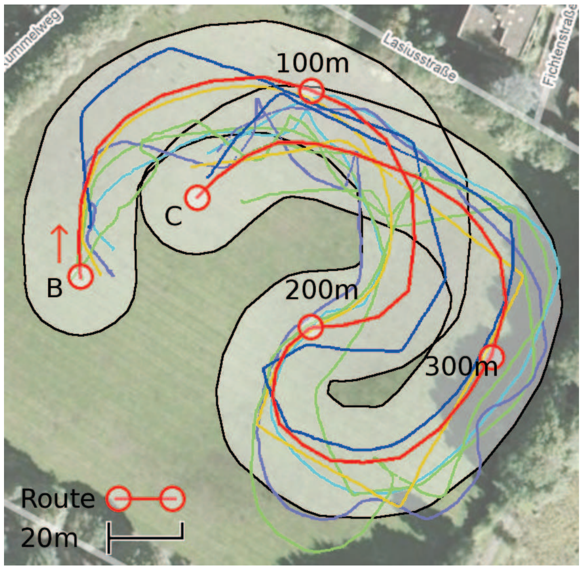


Figure 10: The second route from point B to C and the tracks walked by the participants. A 15m corridor around the route is highlighted.

7.2.2 Observations

Six of the seven participants were able to follow both routes till the respective end. One participant was not able to complete the routes due to technical problems of the PDA application. The results from the six participants finishing both routes are described in the following.

Figure 9 shows the first route, the six paths walked by the participants, and a 15m corridor around the planned route. The average distance covered by the participants to follow the 375m long route was 338m. The shortest distance was 317m and the longest distance was 362m. The participants needed between 4:52 minutes and 7:43 minutes (6:40 minutes on average) to complete the first route. The average walking speed was 3 km/h. According to the recorded positions the deviations from the route were computed. The distribution of the percentages users walked with a given deviations are shown on the left of Figure 11. The maximal deviation from the route was 18.25 meter and the average deviation was 6.57 meter. About 99% of the recorded positions had a deviation of 15 meters or less and 78% had a deviation of less than 10 meters.

Figure 10 shows the second route along with the paths walked by the participants, and a 15m corridor around the route. The average distance covered by the participants to follow the 430m long route was 455m. The shortest distance was 395m and the longest distance was 524m. The participants needed between 7:04 minutes and 9:37 minutes (8:13 minutes on average) to complete the second route. The average walking speed was 3.3 km/h. The distribution of the portions users walked with a given deviations are shown on the right of Figure 11. The maximal deviation from the

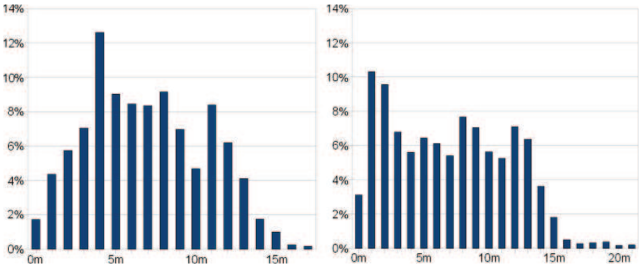


Figure 11: Portion of the path walked by all users with the respective deviation in meters. First route is on the left and the second route on the right.

route was 22.85 meter and the average deviation was 7.21 meter. About 99% of the recorded positions had a deviation of less than 20 meters and 95% had a deviation of 15 meters or less.

According to the collected questionnaires participants mentioned that the belt would benefit from more compact hardware to improve the wearing comfort. This mainly referred to the cables and the size of the box containing the electronic components of the tactile display. In addition, participants thought to experience fluctuations of the tactile presentation at times. However, overall the participants had a positive impression of the developed presentation. They mentioned that the presentation is intuitive especially after gaining some experience and appreciated that they could use both hands for other tasks.

7.2.3 Discussion

The evaluation shows that the tactile belt enables user to follow routes on open fields without any visual landmarks using tactile feedback only. The participants average walking speed was slightly slower than the speed of a normal pedestrian, however, all participants were able to walk at relatively constant speed. Even though, a waypoint was treated to be reached if the user was still 15 meters away, the participants stayed inside the 15m corridor around the route with only three exceptions. Since the direction presentation proofed to be independent of visual landmarks, we expect it to work even better in environments that allow orientation at visual landmarks. A remarkable aspect that we observed is the participant's generally low deviation from the route, even though the first evaluation showed that participants express perceived directions with a deviation median of 15°. In the following we discuss two other reasons causing the remaining inaccuracy.

The first found reason is the used guidance technique. The system switches to the next waypoint of the route if the user is closer than 15 meters to a waypoint. Thus, the displayed waypoint is always further away than 15 meters and the user is not guided directly but only very slowly back on the route. We analyzed this effect by reducing the diameter of the waypoints from 15 to 5 meters and tested the system with an additional participant. The average deviation from the route for this participant was 2.29 meters with a maximum of 6.51 meters which is less than a third of the average deviation of the other participants. This test can be seen as a clear indicator that further lowering the waypoint radius results in much more accurate guidance.

The second reason we found is the inaccuracy of the used localization technique. The participants' average deviation from the route was about seven meters and it can be expected that the accuracy of the GPS localization was up to ten meters [1]. Thus, the participants' average deviation is comparable to the inaccuracy caused by the localization technique. It can be concluded that the participant's deviation is at least partially caused by the localization inaccuracy. Using a more accurate localization technique (e.g. the European Galileo system) would therefore reduce the user deviation from the route. In addition, in situations were the user can additionally orient on landmarks (e.g. the street layout) the localization technique's influence of the deviation should further reduce. In general our observations cannot show which fraction of the user's deviations is caused by the participants perception and which fraction is caused by the used localisation system. However, since GPS is the most accurate outdoor localization system that is available other outdoor navigation system share the problem caused by the localization errors.

7.3 Summary

In this section two evaluations of the tactile wayfinding systems were described. The first evaluation showed that users can perceive presented directions with a median deviation of 15° from the presented direction. The second evaluation showed that the developed support system for wayfinding is able to guide users along routes without additional feedback. Based on the observations in both evaluations promising approaches were identified to further improve the non-visual support system for wayfinding.

An aspect that must be taken into account is the specific use case addressed in the evaluations. Areas with no or few visual landmarks are, for example, not typical for urban environments. On synthetic routes that do not correspond with the layout of the respective area users must solely rely on the tactile feedback. In urban environments pedestrians and cyclists and can use visual landmarks and the area's layout to complement the tactile feedback. We evaluated the system without visual landmarks to avoid unnecessary side-effects. We expect that in urban environments the users' performance in terms of deviation from the route would greatly increase.

8. CONCLUSIONS AND FUTURE WORK

In this paper we described the Tactile Wayfinder, which is a travel aid supporting wayfinding in unfamiliar environments. It applies sense of touch to guide the user on a planned route. A spatial tactile display worn as a belt conveys the necessary information non-visually, non-intrusively, and hands-free. The system is therefore appropriate for all people moving in unknown areas, such as pedestrians, bikers, or even blind people. It was designed with a high attention on the cognitive demands during wayfinding and the specific mobile user situation. Any deviation from the path is presented immediately and gently. There is no need to interact with the system explicitly. Thus, the user is able to concentrate on other tasks like obstacle and hazard detection. We have developed a first prototype to enable evaluations with end-users. Two evaluations showed that the Tactile Wayfinder is a successful approach for guiding. In the first evaluation participants perceived a direction presentation by a mean accuracy of 15°. The second evaluation proofed that the Tactile Wayfinder keeps the traveler within a specified corridor of a pre-defined unknown route without any landmarks. The evaluations also revealed potential improvements for further developments regarding the system design, stability, and also the algorithms to guide people from one waypoint to another.

Besides the refinement of the system based on the evaluation results, we plan further evaluations to find out specific configurations for guiding the user in different situations, for example in urban environments, buildings, national parks, while riding a bike, or driving a car. Additionally, we plan to enhance the system to provide information other than waypoints, such as points of interest or landmarks along the route. These could be encoded through different tactile patterns and conveyed to the user.

Acknowledgments

This paper is partially supported by the European Community's Sixth Framework programme within the projects ENABLED[1] and InterMedia[2]. We especially thank all participants of our evaluations.

9. REFERENCES

[1] D. Ahlers, D. Wichmann, and S. Boll. Gnss quality in pedestrian applications: A developer perspective, 2008.

[2] I. Aslan and A. Krüger. An advanced pedestrian navigation system. In *Workshop on Artificial Intelligence in Mobile Systems(AIMS) at UbiComp*, pages 15–19, 2004.

[3] R. M. Downs and D. Stea. *Maps in Minds: Reflections on Cognitve Mapping*. Harper and Row, Publishers, Inc., 10 East 52rd Street, New York, N.Y. 10022, US, 1977.

[4] J. B. F. V. Erp, H. A. H. C. V. Veen, C. Jansen, and T. Dobbins. Waypoint navigation with a vibrotactile waist belt. *ACM Trans. Appl. Percept.*, 2(2):106–117, 2005.

[5] R. G. Golledge, editor. *Wayfinding Behavior: Cognitive Mapping and Other Spatial Processes*. The Johns Hopkins University Press, Dec 1998.

[6] S. Holland, D. R. Morse, and H. Gedenryd. Audiogps: Spatial audio navigation with a minimal attention interface. In *Proceedings of Human Computer Interaction with Mobile Devices*, volume 6, pages 253–259, London, UK, 2002. Springer-Verlag.

[7] Humanware. Trekker. `http://www.humanware.com/en-new\_zealand/products/gps/trekker`, last visited 01.Feb.2008.

[8] C. A. Lawton. Gender differences in way-finding strategies: Relationship to spatial ability and spatial anxiety. *Sex Roles*, 30(11–12):765–779, Jun 1994.

[9] S. Long, R. Kooper, G. Abowd, and C. Atkeson. Rapid Prototyping of Mobile Context-Aware Applications: The Cyberguide Case Study. In *2th ACM Interantional Conference on Mobile Computing and Networking*, pages 97–107, Rye, New York, USA, 1996.

[10] E. Platzer. *Spatial Cognition Research: The Human Navigation Process and its Comparability in Complex Real and Virtual Envrionments*. PhD thesis, Universität der Bundeswehr München, 2005.

[11] G. Pospischil, H. Kunczier, and A. Kuchar. LoL@: a UMTS location based service. In *International Symposion on 3rd Generation Infrastructure and Services*, Athen, Greece, 2001.

[12] J. L. Prestopnik and B. Roskos-Ewoldsen. The relations among wayfinding strategy use, sense of direction, sex, familiarity, and wayfinding ability. *Journal of Environmental Psychology*, 20:177–191, 2000.

[13] E. Rukzio, A. Schmidt, and A. Krüger. The rotating compass: a novel interaction technique for mobile navigation. In *CHI '05: CHI '05 extended abstracts on Human factors in computing systems*, pages 1761–1764, New York, NY, USA, 2005. ACM.

[14] S. Timpf, G. S. Volta, D. W. Pollock, A. U. Frank, and M. J. Egenhofer. A conceptual model of wayfinding using multiple levels of abstraction. In A. Frank and U. Formentini, editors, *Proceedings of Theories and Methods of Spatio-Temporal Reasoning in Geographic Space*, volume 639 of *Lecture Notes in Computer Science*, pages 348–367. Springer-Verlag, 1992.

[15] K. Tsukada and M. Yasumrua. Activebelt: Belt-type wearable tactile display for directional navigation. In *Proceedings of UbiComp2004*, pages 384–399. Springer LNCS 3205, 2004.

[16] B. Tversky. Cognitive maps, cognitive collages, and spatial mental models. In A. Frank and I. Campari, editors, *Spatial Information Theory: A Theoretical Basis for GIS, Proceedings COSIT 1993*, Lecture Notes in Computer Science, pages 14–24. Springer Berlin - Heidelberg, 1993.

[17] J. S. Zelek, S. Bromley, D. Asmar, and D. Thompson. A haptic glove as a tactile-vision sensory substitution for wayfinding. *Journal of Visual Impairment & Blindness*, 97(10):1–24, October 2003.

[1] FP6-2003-IST-2-004778
[2] FP6-2005-IST-038419