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Diplomarbeit

NaviRadar: A Novel Tactile Information Display for Pedestrian Navigation

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Zusammenfassung

Die vorliegende Arbeit präsentiert NaviRadar, eine Interaktionstechnik für Mobiltelefone, die mithilfe einer Radarmetapher und taktilem Feedback Navigationsanweisungen für Wegpunkte entlang einer vorgegeben Route angibt. Der Radar rotiert dabei im Uhrzeigersinn, und Vibrationen zeigen an, wenn er die momentane Richtung des Nutzers oder die Richtung, in die der Nutzer gehen soll, scannt. In einer ersten Nutzerstudie wurde das Gesamtkonzept untersucht. Außerdem wurden verschiedene taktile Parameter daraufhin getestet, die beiden angegebenen Richtungen einfach zu unterscheiden und dabei zusätzlich die Entfernung bis zur nächsten Kreuzung zu kommunizieren. Die Ergebnisse zeigen, dass das NaviRadar Konzept einfach zu verstehen ist, und beliebige Richtungen mit einer durchschnittlichen Abweichung von 37° erkannt werden können. Dabei erwiesen sich verschiedene Rhythmen am besten geeignet um die beiden Richtung zu unterscheiden, während die Entfernung durch die Intensität der Vibrationen dargestellt werden kann. In einer zweiten Nutzerstudie wurde NaviRadar in einer realistischen Navigationssituation mit zwei anderen nicht-visuellen Navigationssystemen verglichen. Hinsichtlich Benutzbarkeit und Navigationsleistung zeigte NaviRadar ähnliche Ergebnisse wie Sprachanweisungen, während es in Bezug auf Fehler und Desorientierung bessere Ergebnisse erzielte als ein anderes, auf Vibrationen basierendes Navigationssystem. Dadurch, dass sich die Bedienoberfläche auf taktiles Feedback beschränkt, bietet NaviRadar klare Vorteile gegenüber derzeit gebräuchlichen Navigationssystemen. Der Nutzer kann sich auf die Hauptaufgabe "Gehen"konzentrieren, da NaviRadar keine visuelle Aufmerksamkeit erfordert. Da keine Sprach- oder Tonausgabe erfolgt, kann NaviRadar auch in lauten Umgebungen genutzt werden, und der Nutzer kann wichtige Umgebungsgeräusche wie herannahende Autos wahrnehmen.

Abstract

This thesis introduces 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 whenever the radar scans the user's current direction and the direction in which the user must travel. A first, indoor study evaluated the overall concept. Moreover, six different tactile patterns were compared to communicate the two different directions and the distance to the next turn. 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. Communicating directions via different rhythms and distance with intensity showed to be the most distinct combination, so this setting was used in a second, outdoor study, where NaviRadar was compared to two other non-visual systems in a realistic navigation task. NaviRadar achieved similar results in terms of perceived usability and navigation performance when compared with spoken instructions, and less error and disorientation events when compared with another system using a interface based on vibrations. By using only tactile feedback, NaviRadar provides distinct advantages over current systems. In particular, the user is able to concentrate on the main task of walking as visual attention is not required. Moreover, the lack of needed audio attention enables it to be used in noisy environments and to concentrate on environmental sounds like approaching cars.

Aufgabenstellung

Mobile Navigation wird immer populärer, nicht zuletzt seit Nokia mit Ovi Maps und Google Maps kostenlose Navigationssoftware mit Routenführung für ausgewählte Mobiltelefone mit integriertem GPS Sensor anbieten. Besonders im Bereich Fußgängernavigation bestehen Navigationslösungen aber häufig noch daraus, Stadtpläne von der Papierversion direkt auf das elektronische Medium zu übertragenen, ohne dabei den geänderten Anforderungen und Möglichkeiten gerecht zu werden. Das Hauptprobleme besteht dabei darin, dass dem Benutzer auf einem kleinen Bildschirm sehr viele Informationen präsentiert werden, und dadurch weniger Aufmerksamkeit für die direkte Umgebung, wie den Verkehr oder Hindernisse im Weg, zur Verfügung steht. Im Rahmen dieser Diplomarbeit soll ein Navigationssystem entworfen, implementiert und evaluiert werden, das sich auf die Vermittlung der wichtigsten Informationen, Abbiegerichtung und Distanz, beschränkt, und diese mittels Vibrationen kommuniziert, und damit den bisher wenig genutzten haptischen Wahrnehmungskanal verwendet. Dazu soll zunächst eine Analyse existierender Produkte und Forschungsarbeiten im Bereich Navigation und taktiler Bedienoberflächen durchgeführt werden. Mit diesem Hintergrundwissen sollen geeignete Vibrationspattern entwickelt werden, mit denen die oben genannten Informationen präsentiert werden können, und mit einem ersten Prototypen zunächst noch ohne Navigationsfunktion die Verständlichkeit dieser Signale getestet werden. Mithilfe dieser Ergebnisse kann das Gesamtkonzept sowie die getesteten Pattern kritisch betrachtet, und das Feedback weiter verbessert werden. Anschließend soll das entwickelte Navigationskonzept mittels eines High-Fidelity-Prototypen in einem realistischem Umfeld mit anderen Navigationssystemen hinsichtlich Navigationsleistung und Benutzbarkeit verglichen werden.

Konkrete Teilaufgaben:

- Analyse des gegenwärtigen Standes der Technik und Forschung
- Konzeption eines ersten Prototypen zur Evaluierung verschiedener Vibrationspattern
- Entwurf einer vergleichenden Benutzerstudie und Durchführung mit Hilfe des Prototypen
- Entwicklung und Implementierung eines High-Fidelity-Prototypen
- Entwurf einer vergleichenden Benutzerstudie und Durchführung mit Hilfe des Prototypen

Ich erkläre hiermit, dass ich die vorliegende Arbeit selbstständig angefertigt, alle Zitate als solche kenntlich gemacht sowie alle benutzten Quellen und Hilfsmittel angegeben habe.

München, 27. September 2010

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Contents

1 Introduction

1.1 Motivation

Mobile navigation has become popular in the last decade. In Germany alone, more than 4 million pure navigations devices have been sold in 2008 and 2009 [86]. Additionally, Gartner Research predicts that in 2010, 28% of all mobile phones sold will have GPS capability [89], yet increasing the number of possible navigation devices as device manufacturers like Nokia or internet players like Google now even offer navigation systems for free. Most pure or embedded systems offer a separate pedestrian mode. Typical use cases for pedestrian navigation are the wayfinding in foreign cities, for instance finding an address in a pedestrian area after being guided from the car navigation system to a parking. But also for one's home town it might be interesting if systems incorporate public transport schedules and can guide the user to the best (not necessarily next) bus or train station [3]. For joggers, an integrated training coach could guide the way according to the form on the day, and visually impaired people can be supported in safely getting from A to B. However, interaction concepts have mostly been just taken from car navigation where different conditions apply, such as the vehicle interior is barely influenced by the outside noise level, but is more like a private space, or the installation of a navigation system is fixed and not constantly moving like a device held in the hands. When being physically mobile, a single glance on the screen will often not be enough to provide the user with the required information, as navigation interfaces usually are complex, provoking the typical "heads-down" usage of mobile devices. This takes away attention from other tasks, like caring about the surrounding, and slows down the walking speed. Speech interfaces provide non-visual turn-by-turn instructions and are very popular for in-car navigation, but they have different drawbacks for pedestrian navigation. In a noisy street environment, it might be difficult to listen to instructions, while in a quiet setting, audio feedback can be embarrassing if other people have to listen to it, too. Alternatively, headphones can help with these issues, but they cut off from environmental sounds like approaching cars and make it difficult to walk within a group as wearing headphones might be considered as rude and isolating from the rest. Moreover, speech instructions are slow to use and attention demanding, as information is given sequentially and at a specific point in time, with mostly no way to have an instruction repeated. Therefore, an alternative channel for providing pedestrians on the go with turn-by-turn instructions is investigated in this thesis, the usage of a tactile interface.

1.2 Idea

The idea is to use the sense of touch as an additional perception channel, as its capacity is neglected so far. The idea is to walk along a route, intuitively guided by vibrations. Those can for instance be created by an add-on for navigation systems running on mobile phones, using a standard phone vibrator. By listening to the vibrations that differ in several parameters, the user knows where to go and at the same time is able to walk with his full visual and auditory attention for the environment. The main concept behind the system called NaviRadar is to imagine a radar rotating constantly around the user. With every circulation, it scans two directions: the front and therefore current heading of the user, and the direction in which the user must travel at the next crossing. The user is able to differentiate between the two directions as they are presented as distinct vibrations. The always indicated front pulse allows to build up a feeling for the rotation speed, whereas the other vibration is used to communicate the turning instruction. By interpreting the offset between vibrations, the direction to travel can be perceived.

Figure 1.1 shows an example of the indicated directions where the user has to go right, right and left. The radar movement is indicated by the arrow on the circle around the user. For instance, at the first position before the first right turn, the user perceives the vibration for the current direction (D_C) and then, after less than a quarter of the whole circulation time, the vibration for the desired

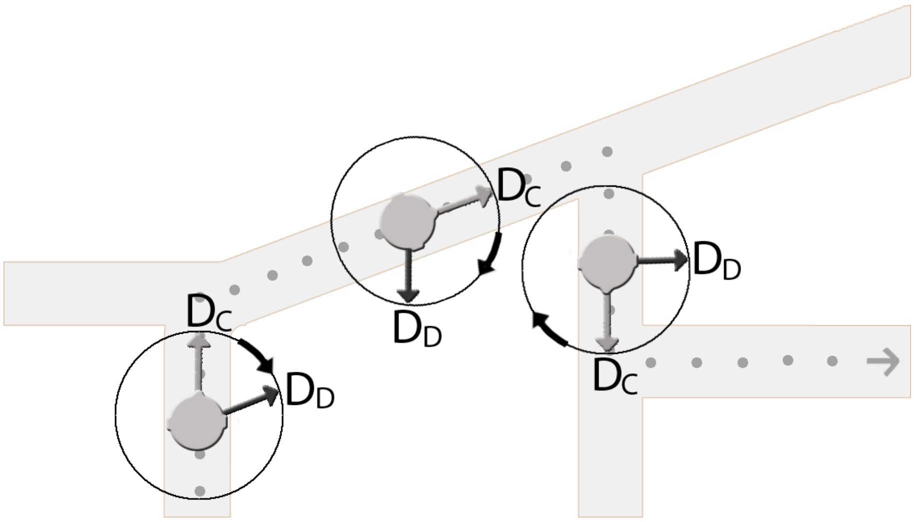


Figure 1.1 – NaviRadar concept, illustrating a path where the user has to go right, right and left (D_C - current direction, D_D - direction desired)

direction (D_D). On the other hand, at the last position, where a left turn is required, D_D is indicated, and then after a quarter of the rotation time, the vibration for D_C can be perceived.

1.3 Outline

This work investigates the design, implementation and evaluation of NaviRadar. The conceptual background of the work is discussed in Chapter 2 and 3, that refer to different aspects of pedestrian navigation with vibrational feedback, while Chapter 4-6 refer to the development and testing of a prototype application in two user studies.
Chapter 2 introduces to navigation in general and resulting different wayfinding strategies, and identifies the information that needs to be communicated for successful wayfinding. Requirements for navigation systems and an analysis of existing solutions are presented, and an introduction to context-sensing, including a comparative test between two different compasses, is given. Chapter 3 starts with an introduction into human perception and the parallel processing of multimodal information. A definition of tactile feedback and arising potential of the use of vibrations is presented. Moreover, an overview over existing research using rich tactile interfaces is given, with a focus on navigation and orientation tasks. Tactor technologies and emerging parameters are introduced in Chapter 4. Moreover, the development process of vibrational patterns is shown, and emerging settings for distinct vibrations are described. Chapter 5 discusses a first user study that tests the main concept and compares six different vibration patterns in a controlled laboratory environment. Chapter 6 reports a second study conducted outdoors, where the performance of NaviRadar is investigated in terms of usability and error rate in a realistic walking test, compared to another tactile and an audio system. The thesis closes with a conclusion in Chapter 7, summing up the outcome of the user studies and giving a motivation for future work in the area of pedestrian navigation and the design of tactile interfaces.

2 Navigation and wayfinding

The following section gives an introduction into the field of navigation. First, the process of navigation and wayfinding is defined, and a classification of knowledge and characteristics of navigation information is presented. Then, human requirements and capabilities, especially in terms of mobile usage and physical impairments, are discussed. A review over commercial navigation systems including solutions for the visually impaired is presented. As navigation is a dynamic process, the last subsection introduces into the field of context-sensing, concerning application areas as well as concrete sensors.

2.1 Definition

Navigation systems support people in a wayfinding task. They need to determine how to get to a destination and which activities are needed to go there. Different information can already be available from the environment [93] which has to be processed and pieced together, like architecture, signs, or even other people. Navigation systems help to make use of them or provide additional instructions. Ross and Blasch [78] distinguish between mobility, spatial orientation and wayfinding. Mobility is the coordination of actions to move, while spatial orientation is needed to coordinate for further-ranging surroundings and to maintain the awareness of one's position relative to the environment. Wayfinding is then defined as employing this orientation to maintain a heading up to a main target, while mobility is achieved incorporating feedback from the environment about dynamic changes like obstacles on the way. The whole wayfinding task consists, according to Kray et al. [49], of several steps:

$$\text{Orientating} \rightarrow \text{Selecting} \rightarrow \text{Keeping} \rightarrow \text{Reaching}$$

As a first step, the origin and destination location have to be determined. From this information, one or more route suggestions can be computed, based on criteria like shortest or fastest way. There have been huge improvements due to improved technologies such as processing power, positioning, or mobile transfer rates [58], leading to more sophisticated solutions even including public transport. As soon as the desired route has been chosen, and the user is on his way, the route has to be maintained, and single decision points are passed. One possible way to support this process is to use an interactive map where the current position is moving according to positioning data, another one would be to present turn-by-turn instructions. As a last step, the user has to be informed when the destination has been reached.

Knowledge classification Different kinds of knowledge can be incorporated into wayfinding. *Route knowledge* describes an understanding of the environment in terms of paths between waypoints [58], and is efficient to navigate as one just has to follow this description by monitoring the current position, and the distance to the next decision point. However, problems occur when technical means fail and the user gets lost, so the given route can no longer followed and a self-dependent recalculation of route data is required [37]. In contrast, *survey knowledge* provides a more global view, where not a single route, but the whole environment is integrated. The navigation can be more flexible as one has an overview over the whole area and can, from the actual position, predict spatial relations and dynamically build up the route to walk [50]. This knowledge is built up automatically by active exploration of an area or reading maps, and stored as a cognitive map, a mental image of the area which can be used as a basis for autonomous wayfinding decisions. Research in this area focuses on how individuals acquire, learn, develop, think about and store data and then analyse what and how information has to be presented to support this process [6]. It can be reduced when using turn-by-turn guidance [50]. Overall, the cognitive load is higher than following given instructions. Another category is *landmark knowledge*. Landmarks

are conceptually and perceptually distinct locations [58], that are mostly a combination of type (e.g. shop, crossing) and concrete description (e.g. colour, size). They can be used to orientate oneself and localise certain places, and therefore confirm route knowledge and organise spatial knowledge. It can, however, not be used to find and select a route [37]. A further difficulty with landmark knowledge is that it is hard to describe, as for everyone other things are important, depending on individual experiences.
Vainio [105] identified two different navigation strategies emerging from these categories: with route-based navigation, people rely on instructions where and how to turn, whereas orientation-based navigation describes a wayfinding process that is based on the current position relative to reference points where finding the way is realised according to this information. In the following, main attention is paid to the first, route-based navigation, and the provision of turn-by-turn instructions, as this allows the navigation task being accomplished more effectively and by the way, especially in unknown areas, than relying on survey knowledge and figuring out the way by oneself.

2.2 Navigation information

Different information can be presented to support a navigation task. In the following, characteristics of crossings and differences between car and pedestrian navigation are described, and an overview over possible instructions is given.

2.2.1 Classification of crossings

Before thinking about what and how navigation information has to be conveyed, this section shows possible use cases for a single decision point. In Figure 2.1, some exemplary crossings are shown. Crossings can differ in various parameters. The complexity of a crossing is mainly influenced by

Figure 2.1 – Selection of different types of crossings

the *number of possible turns*. To define a crossing, at least two turns are available, but it can also be up to five or more, making the decision more difficult as several branches then point to a similar direction. Moreover, the *kind of turns* are part of the characteristic of a crossing. Turns can go straight, or at least lie in a certain interval around the front direction, or point to the left or right. In that case, slight, normal and sharp turns can be distinguished, depending on the degree of bending. The complexity of a crossing is then influenced by the *combination of turns*. An easy combination would be a 90° turn to the left and right, while a more complex crossing could incorporate several turns to one side. A further influencing factor is if turns emerge from a common spot or if the beginnings of two new streets are slightly shifted, as shown on the far right of Figure 2.1. It has then to be decided if that is regarded as one big or two small crossings. A special case, in particular relevant for pedestrian navigation, are *large spaces* with no predefined paths, such as parkings, or places, where multiple ways out are available (see Figure 2.1, second from the right).

2.2.2 Differences between car and pedestrian navigation

Navigation systems for cars are nowadays widely established. For pedestrian navigation, concepts are often just adopted, however, there are differences in the underlying requirements. At the end of the previous section, one difference between pedestrian and car navigation has already been mentioned: pedestrians often encounter large walking spaces with no predefined lanes, where they have to find their own way and that have to be treated differently than clearly defined streets [119]. Moreover, pedestrians can more easily find shortcuts, have a rest or turn over than it is possible when driving a car [4]. Also, pedestrians walk much slower than cars are driving (approx. 5 m/s vs. 50 km/h), therefore the timing of instructions has to be adjusted. A further difference lies in the availability of sufficient positioning data. In most cases, pedestrian ways are narrow streets or paths allowing less variance than a wide road, moreover, especially in city centres, they lie between tall buildings where GPS signals are disturbed by multiple deflexions [50].

2.2.3 Information to be presented

A broad range of information is available to be presented by a navigation system. Table 2.1 shows possible categories and examples.

As most navigation systems are map-based applications, common information to be represented

Category	Example
Map	Route Current position Already walked way
Next step	Indication that a turn is close Direction to go Distance left Striking landmarks
Step after next	Direction to go Distance left
Further indications	Destination reached Turn over required
Overall values	Overall direction to the destination Distance left to the destination Estimated time to reach the destination
Additional information	Current street name Current speed Points of interest (POIs) around

Table 2.1 – Possible information to be presented by a navigation system

is the route one has to go, and the current position on the way. Sometimes, the already walked part is marked differently. When talking about turn-by-turn navigation, the user is notified when the next turn is coming up, for instance by beeping, vibrating, or simply showing something on the screen. This can be done some time before the crossing is reached for preparation, and additionally when the turn is close. Concrete information mostly refers to the direction one has to change to. Additionally, the distance in metres or distance classes ("in 50 metres", "now") can be given to allow the user to estimate the remaining time to walk before turning. Latest navigation systems also show striking landmarks to help matching the information presented with the environment [58]. Indications like that the destination has been reached or the user has turned towards the wrong direction are further important information, while the overall direction, or additional information such as POIs (sights, shops, restaurants, pubs) are not critical for a navigation task where the primary goal is to reach a specific destination. From the analysis of existing navigation solutions for the visually impaired, some other interesting aspects and requirements that can be incorporated in a navigation system have been identified. Particularly important for visually impaired people is constant feedback, that notifies the user immediately if the route has been left, if there are problems with the positioning data or if the route needs to be recalculated. Another wanted feature is to allow to save and reload routes, and to explore a route virtually before actually walking.

May et al. [58] examined the information requirements for pedestrian navigation. They asked two groups of participants to identify the information needed to navigate certain routes. The "cognitive map group" relied on their memories of the area already acquired before the study, whereas participants of the "walkthrough group" made up the instructions being led along the route. Collected instructions were then examined and categorised in terms of *what kind of information is used* (landmarks, distance, path type, junction, street name), *how* (to preview, identify, or confirm) and *when* (at a decision point, on the way) this information is applied. Most of the time, and by both groups, landmarks were chosen for the instructions. In 2/3 of cases, instructions were given to identify a decision point and give concrete turning advices, such as "Turn left past the supermarket". Other categories were used infrequently by both groups. Furthermore, one third of instructions was given along the paths to confirm the way, indicating that a regular feedback is useful to maintain trust in the current heading.

Transferring the importance of landmarks to identify a decision point to a system providing live turn-by-turn instructions, the information loses importance as the timing of instructions already determines the location. Moreover, this kind information is not yet available for most places, especially for a different modality than visual, such as would be for instance oral descriptions of buildings. More common is, for example in audio guides, the indication of direction at the appropriate time, and to include distance ("After 50 metres, turn left"), to allow the user to prepare for the turn. This approach is also taken in most of the research projects described in Chapter 3.6 (e.g. [71], [55], [103], [106], [35]). The two values direction and distance are therefore chosen for the navigation system presented in this thesis (see Chapter 4.4 for the concrete realisation).

2.3 Human capabilities and requirements

To develop a successful navigation interface, it is important to know how people can perceive instructions, and what kind of factors can influence their abilities, like being mobile, or having limited eyesight.

Spatial ability According to Vainio [105], humans can be classified regarding their preferences concerning spatial anxiety and spatial knowledge. These can influence the ability to navigate, like spatial anxiety, that describes when someone feels anxiety when being in an unfamiliar area, can lower the navigation efficiency by being unsure and double checking every decision. A general problem of the usage of navigation systems with turn-by-turn instructions is that users do not make an effort to acquire spatial knowledge. However, when technical problems or dynamic changes like impassable paths occur, reorientation fails because of the lack of this knowledge. It is therefore important to support the acquisition by making users aware of the environment and their way through it. One way might be to use overview maps, another to allow maximum concentration on the surrounding by providing instruction as unobtrusive as possible.

Gender Different research has shown differences between women and men regarding navigation and orientation. Female participants performed worse in acquiring landmark knowledge when landmarks were presented with oral instead of visual cues, where men did not show any differences, indicating that the combination of different modalities causes problems [50]. According to

Lawton [52], women prefer a wayfinding strategy based on route knowledge with concrete turning instructions while men prefer a survey knowledge strategy like keeping track of the own position on a map. A navigation system favouring the one or the other strategy might not show the same performances among men and women. For instance, Pielot et al. [67] who used a tactile belt to present the current direction, report worse results for female participants. They took longer, made more errors and lost the orientation more often.

Human-human interaction pattern In-vehicle navigation is often accomplished by two people: a driver and a navigator, who reads the map and gives instructions. Forlizzi et al. [30] examined these collaborative interactions to gain insight how interfaces of navigation systems could be improved, since commercial in-vehicle navigation systems do not allow much interaction. The three main areas they were interested in were how different teams collaborate, if a social relationship has an influence on the interaction and if specific patterns of interaction can be identified.
Participants often discussed passed landmarks while driving, but not always related to the navigation task. Mostly this was done to increase the meaning of places to remember them in future navigation tasks. Especially in teams where parents and their children were driving, this was done to enhance survey knowledge. One pattern was that often the next step of the route was not only given when the turn was close but also directly after finishing the preceding step, in order to give the driver an idea of when the next manoeuvre has to be taken and what it will look like. It also emerged that the timing of instructions is often dependent of the position of the vehicle relative to the route and the next turn to take. There are a lot of other influencing factors, like speed, state of traffic lights or other environmental conditions. To overcome this complexity which can cause the navigator to not give the instructions at the right time, the driver also asks for information when he thinks he needs them. Overall implications that arise are that information for the driver has to be flexible and adapted to the current context, and the driver's existing knowledge should be incorporated in the information delivery.

Preference for nice, not short ways Pedestrians who are as tourists in a foreign city often regard their trip from A to B as a leisure activity, and prefer to find nice ways and new places, so a navigation system that is fixed onto the shortest path might not be the first choice. Poppinga et al. [72] examined this situation, and developed *Tacticycle* to support an explorative behaviour while cycling by not giving turn-by-turn instructions but constantly indicating the overall direction to a destination and the location of near POIs on a tactile display. Requirements they were trying to meet were to provide orientation help as well as planning trips on-the-fly. To support finding new interesting places, hints have to be given to indicate their presence. To get more detailed information about a POI the user has to touch it on the visual display. Positive aspects like increased environment awareness and the reduced need to explicitly demand orientation and spatial information were mentioned by all of the participants.

Mobile usage Navigation systems can be used to plan routes in advance, however, the main application area is when being mobile. But the usability often decreases when applications are just "ported" from the desktop-pc, as differences to stationary use exist in several aspects. A *mobile device* is most of the times smaller than a stationary one [75], and input methods may be limited. *Environmental factors* like light that reflects [67] or brightness that changes [114], as well as noisy [114] or particularly quiet environments [39] can restrict the usage of audio output and therefore influence the usability. Another aspect is the *mobility* itself, which causes the device to be shaken and therefore display contents are harder to be recognised [85]. The *mapping* of information on the screen and the real environment can be a problem [75], as real impressions have to be compared to virtual representations. *Social factors* like being in a group where looking concentrated on the mobile phone is seen as separating from the others [98], is another speciality of mobile usage. *Shifted attention* also influences mobile usage, as other tasks like being mobile and walk around itself have to be fulfilled, too [116] [63] [79]. Tamminen et al. [98] monitored human actions in social life and found that navigating through an urban environment requires paying constant attention to surroundings and limits attentional resources available for interacting with a device. Also, they pointed out the fluctuation in importance of time and place that they call temporal tensions. Those affect the task scheduling strategy for occupying the user's attention. When people are hastened, they have to perform multiple tasks more or less simultaneously. The priority of the tasks changes and pre-scheduled tasks can become impossible for a moment. Instead, users start to direct their attention to other, more urgent tasks, therefore, application designers have to take into account that users are not always fully concentrated on a single application. Oulasvirta et al. [63] examined the differences of attention shifts in different time pressure conditions and laboratory as well as realistic outdoor settings. They could show great, partially up to eight-fold, differences in the time someone concentrates on the screen and context-switches during waiting in a laboratory settings compared to a mobile setting where participants stood under high time pressure. They spot different strategies people develop to cope with the mobile situation. One is to *calibrate the attention early on* where people try to predict future distortions to be able to allocate their attention to the most important task. Brief sampling over long intervals can be used to check an interface for progress, while the main attentions stays on the environment. During *task finalization*, people try to keep attention to their mobile device until the task is finished, while *turntaking capture* describes when social interaction is so demanding that is completely overrides the concentration on the task, and then long breaks occur before looking back to the screen. To overcome the problem of unsuitable interfaces while walking, Yamabe et al. [115] [116] developed a navigation system that adapts to the current situation and applies weighted importance to information depending on the situation. Their principles are *simplicity*, meaning that only information should be presented that is important in the current situation, *multimodality* to address the most appropriate sense, and *adaptability* to adjust the mode of presentation according to the given context.

Visual impairments Visual impairment describes the loss of vision resulting in a significant limitation of visual capability. Additional problems occur while navigating as information, perceived by the way by sighted people, is missing, like the awareness of obstacles on the way, remaining distances to a crossing or the presence landmarks, and sufficient databases containing all that information are not yet developed [6]. Alternative channels need to be used, however, for instance using sound prevents the perception of other important ambient sounds, and might be difficult in very quiet but also noisy environments [2]. Often, an assistant person is needed to describe the surrounding and help navigating, hindering the visually impaired to be autonomous. Unobtrusive aids, allowing to sense the environment, could increase the social inclusion [35] and make visually impaired people feel comfortable to walk from one location to another.

Bradley and Dunlop [6] conducted a study where two groups of either sighted (condition 1) or visually impaired (condition 2) people created instruction sets for navigating a route. It was investigated whether instructions given by the own group are more helpful than those of the other group. Visually impaired incorporated less information about concrete shop or street names, but in contrast more sensory information like specific smells, or motion information like constantly passing cars. They also included social contact as a form of instruction, indicating that sometimes the easiest way to get the information needed is to ask people for help. They detected differences in the workload of both groups and for the two conditions. Visually impaired people were less frustrated, and required less mental and overall effort, and reached the destination significantly quicker, when being guided by *condition 2* directions. Since *condition 1* contained messages predominantly consisting of concrete names, the explanation for these results could be that there was insufficient information, indicating that existing travel databases need to be augmented for visually impaired travellers in order to incorporate more meaningful information. The sighted group displayed little evidence of being faster for either condition, but did demonstrate a greater mental workload within *condition 2*, especially for frustration, mental demands and effort.

2.4 Navigations systems

Existing navigation systems have been examined regarding common interface types. Furthermore, an overview over commercial systems is presented, considering solutions for the visually impaired, too.

2.4.1 Interfaces categories

Different possible interfaces are used to convey navigation information in commercial and research systems. The following section gives an overview over main modalities and their characteristics.

Interactive maps One popular interface for navigation systems is to use an interactive map, where the position of the user is shown as an icon dynamically adapted according to the current position. This enables a quick overview, and gives a lot of information to be processed at one glance. One approach is to use schematic maps where single important landmarks stand out to easily orientate, instead of showing all available details [49], however, finding out what is important or not may be a problem. Another common approach to reduce the workload is to use dynamically aligning maps instead of a static representation. A static, north-up map always has the same appearance and allows to maintain the overview over a certain area, while a dynamic, heading-up/track-up map frees the user from the effort to rotate the map mentally to map the real environment to the given information and allows quick navigation [91]. However, it can be hard to orientate when the appearance of the map changes while looking away. Seager and Fraser [87] compared performances and preferences when physically, automatically and manually turning the map. They found that participants prefer to align the map themselves, however, a good compromise could be to initiate the auto-align with the press of a button. Another variant to reduce the cognitive workload while using maps is to not show the current position in the centre but on the bottom side of the screen [112]. This only works for heading-up maps. As a mobile device is normally held in front of the body, this egocentric view towards the current heading of the user might be more intuitive than standing in the middle of the map, and as long as the user is already heading towards the correct direction, more useful information is displayed.

Arrows A more simple way to present navigation information visually is to use arrows pointing to the respective direction [49]. In most common navigation systems, an arrow is used additional to a map to present an oncoming turn. By varying the length, distance can be indicated, but to clarify, additional alphanumerical information is needed.

Speech Another common modality to present instructions is to use speech output, where concrete commands like "In 20m turn left" are given. Mostly, the next turn is announced as soon as the previous is reached, and again when the turn is close. The exact distances depend on the current street layout, that is if there are shortly succeeding crossings or spacious streets and distances, and on the current speed.

Sound Another possible interface would be to use sound to guide people to their destination. Holland et al. [43] used spatial audio in their AudioGPS to provide route information, where direction is displayed as the panning position of a briefly repeated tone. An alternative approach for direction was to always present two tones. They are both played at the same spatial location, and as long as the user is going straight towards his destination, they have an equal pitch, but when the angle between current and desired direction gets bigger, the pitch of the second tone is changed, with the maximum of an octave showing a 90° deviation from the way. To communicate distance, a Geiger count metaphor is used; durations of intervals between direction tones indicate the distance to the next indicated waypoint to be aware of a soon to take turn. Additionally, the tone changes as soon as the remaining distance falls under a certain threshold. First tests indicate that the system can be used to reach a destination, and no differences occurred between musicians and non-musicians indicating that no previous knowledge or abilities are needed to use sound to be guided.

Strachan et al. [95] followed a similar approach with GPSTunes. Their navigation did not use spatial audio, but continuously adapted music listened to like on a normal MP3 player. Therefore, the whole music feedback was panned to either left or right to show a direction, and the volume was adapted to show the distance to the destination (louder = closer). In contrast to Holland et al., who only used GPS measurements to obtain the current heading, a compass allowed users to browse for a direction by rotating around the spot and simultaneously listening to changes in panning. Open field tests revealed that the active browsing improves orientation and reduces the variability of walked paths. Adapting music for navigation was also used by the Melodious Walkabout of Etter and Specht [26], who could show that using familiar music instead of arbitrary tracks does not affect the performance, but allows faster learning and is more enjoyable to use.

In ONTRACK, an application by Jones et al. [45], direction was not only coded by a panning of music but also by adjusting volume. When the deviation to the correct route gets bigger, the music shifts to the left or right, and additionally gets weaker. When directing towards the destination, the music shifts back and gets strong again. Moreover, the sensitivity of the system was adjustable to only show great direction errors of 90° or 45°, which is useful in familiar environments, or to adapt to every degree of deviation for areas where no previous knowledge is available. In a comparative user study with one system using speech output and another just using a paper map, ONTRACK achieved the same results regarding completion time, successful arrival and workload. The main problem during the study was that participants were confused whether a waypoint was lying directly in front of them or behind, as stereo sound was used to present the direction. Only the gradually fading out of music made them aware of moving away or towards the next waypoint. Other problems were music tracks that used panning themselves, or the fading in and out between songs.

Tactile feedback Tactile feedback is mainly used as a notification for information presented in other modalities. Research using tactile feedback to give concrete navigation instructions is presented in Chapter 3.6.

2.4.2 Commercial applications

Navigation systems can be classified in three categories regarding the data storage. Onboard systems save map material on the device or memory cards. The access of data is therefore quick and independent of network coverage. Costs are restricted to acquisition and maybe occasional update costs, but no costs from the download of data emerge, especially no roaming costs. In contrast, with offboard systems, maps are always fetched on demand via mobile networks or Wi-Fi. This allows for small memory requirements and always latest map data where often traffic information is included, which can be useful when navigation is only used from time to time. However, it requires a stable data connection and depending on the provider, costs can be incurred for each request, and when using it abroad, roaming costs may accrue. Hybrid systems are a combination of both. This concept is for example used with Ovi/Nokia Map, where map material is preloaded and stored on the device, while latest updates and traffic information are loaded on demand.

Commercial navigation systems, also called personal navigation devices (PND) [67], for cars and pedestrians mainly use interactive maps and give instructions either as indications on the screen, or in the form of audio commands. Auditory and tactile cues are sometimes used to notify the user to look at the screen. Folizzi et al. [30] summarise the main features of these systems as shown in Table 2.2. Current pedestrian navigation systems for mobile phones are offered from mobile

Category	Example
Input	- Enter address or choose a POI - Choose between route suggestions
Unidirectional information flow	- Adapt interface to fit the current context - Only a small area of the entire route is shown
Context sensing	- Automatic recalculation when planned route is left - Incorporate live traffic updates
Interactions (mostly not included)	- Ask for repetition of commands - Control timing of information delivery

Table 2.2 – Main features of common navigation systems

phone providers as well as from traditional suppliers of navigation systems, online companies or device manufacturers. Figure 2.2 shows some example screenshots of common navigation systems. For instance, Vodafone [141] [142] who bought Wayfinder in 2009 offers its own navigation

Figure 2.2 – Screenshots of common navigation systems running on mobile phones: a) Google Maps b) NaviGate 3.0 c) Ovi Maps 3.0 d) Navigon 7

system called *Vodafone Find&Go* (also called *Vodafone Navigator* in Germany) available mainly for Blackberry and Nokia phones, that includes a pedestrian navigation, however, without voice output. T-Mobile Germany offers with NaviGate 3.0 [139] a preinstalled offboard navigation system with daily or monthly price models. Pedestrian navigation has been worked over since the previous version 2.6, but is no longer available for free. It is available for Blackberry, Nokia, Sony Ericsson and Samsung phones. Motorola has also its own on board phone-based navigation system called MOTONAV [129] in cooperation with NavTeq offering pedestrian navigation. Navigon's Mobile Navigator 7 has been developed for Symbian, Windows Mobile, Android and the latest generation of the Apple iPhone [132], and includes multilingual voice instructions for car and pedestrian navigation. Since the latest version, it is now a pure onboard application. TomTom [140] has currently versions for iPhones as well as Windows Mobile phones, that are stored on board. It includes a demo mode where the route can be driven or walked along in advance. Other companies like Route66 [133] (Symbian and Windows Mobile phones) and Garmin [123] (predominantly on their own devices, but also for selected mobile phones) provide mobile navigation with special walking modes, too. Google maps with its free website [124] to plan routes in map or satellite view for either cars, bikes or pedestrians, but without actual turn-by-turn navigation has been the precursor for the now in several countries available, free Google maps navigation [125] for Android phones. Besides standard navigation functionality, it offers Streetview, however, so far only for car navigation. A further free offer has been announced by Nokia in 2010 [74]. Ovi Maps is the replacement for Nokia Maps and now downloadable for all Nokia phones for free. The hybrid system includes 3D views of sights and satellite views, points of interest can be requested on demand. In pedestrian mode, audio guidance can be supported by vibrational feedback to announce an oncoming instruction.

2.4.3 Orientation devices for the visually impaired

Visually impaired people have several non-technical solutions to ease or even allow navigation on their own. The sense of touch can effectively assist them finding their way. Braille characters can be applied to certain places, but it is difficult to know where to search for them [78]. Maps with Braille identifiers can provide an overview over a route including additional information, however, they are bulky to use, and the matching to the real world is difficult [78]. Pin arrays raise specific pins to create Braille characters dynamically [9] and need less space than static devices, but have not yet been used for navigation tasks.
Canes and guide dogs are widely used, but also subtle methods like counting steps or already crossed streets are common. More technical are canes or separate devices with ultrasonic sensors or lasers that detect obstacles (see Figure 2.3 a)) and provide the person with haptic feedback when something is in the way [51]. Systems like TalkingSigns [135] provide the equivalent of visual signage emitted via infrared signals. With screen readers, or if applicable, screen magnifiers, visually impaired people can also make use of mobile navigation systems like the ones discussed before. But there are special applications like Loadstone GPS [128], an open source software for

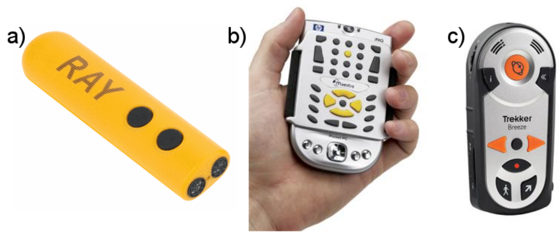


Figure 2.3 – Navigation aids for visually impaired users: a) CareTec Ray, for ultrasonic obstacle detection b) Humanware Trekker c) Humanware Breeze

GPS navigation developed in cooperation with blind people that is running on Symbian phones. One special feature is to save specific points like dangerous crossings, or addresses of friends, and access voice information later when on the way, like how far and in which direction those points lie. Wayfinder Access, that is based on Wayfinder Navigator, offers another system for mobile phones that includes speech output and an interface optimised for screen readers. The "where-am-I" function gives location-based information about the immediate vicinity, and street names can be read out load, replacing the reading of signposts. Humanware produces special devices like Trekker, a smartphone without display but with similar navigation functionality, or Breeze, a small device being used single-handed, also with voice output for describing the surrounding or giving navigation instructions (see Figure 2.3 b) and c)). Mobile Geo, an onboard system for Windows Mobile phones, uses a text-only interface to allow the use of screenreader. Additional to instructions read out load, it offers the possibility to use vibrations for guidance. Those vibrations encode Morse code letter, like *A* and *T* standing for *Approaching Turn*.
A pilot project aiming to improve the conditions for navigation for visually impaired is Nav4Blind [131], where topographic data with an accuracy of 10cm is collected for an area in Germany. Moreover, with the combination of outdoor and indoor positioning technologies, a seamless navigation is planned. It is part of HaptiMap [126], a project active in the Seventh

Framework Programme of the European Community for research, that aims at making maps and location based services more accessible by using several senses like touch, hearing and vision. Further research concerning navigation of the visually impaired are U-Access, MOBIC, Drishti, PONTES, or ODILIA [119].

2.5 Context-aware computing

Context-aware computing aims at adopting feedback according to the current situation. Most of the time, this refers to the location of use, but it can also include social or psychological factors [98]. By combining and processing the results of different sensors, even activities can be recognised [113]. One example for a such a device is SenSay [90], a context aware mobile phone, that uses five different sensors (voice and ambient noise microphone, accelerometer, temperature sensor, and visible light sensor) to detect the user's activity (uninterruptible, active, idle state, normal). A simple application would be to adjust the ringer volume according to the current situation.
When measuring the context and adapting the feedback accordingly, the appropriate modality can also be chosen, like done by Hoggan et al [42], who showed the advantage of either audio or tactile feedback, dependent on different contexts. Tamminen et al. [98] conclude after their investigation of mobile contexts that the mode of mobility should influence the complexity and modality of the interface, as well as the interruption management.
When developing applications that are meant to be executed as a secondary task, like navigation, it is useful to avoid explicit communication as it distracts the user from primary task [37], and the user should be freed from having to concentrate on operating the device all the time, so notifications of the user should be unobtrusive and changes of the feedback automatically be triggered by certain events [65].
Different sensors exist to measure for example environmental (air, temperature) or physiological data (alcohol gas, heart rate). The sensing of RFID signals or the use of camera and microphone data are further areas how information about the surrounding can be gathered [113]. Already included in the latest generation of mobile phones are for example light sensors to adjust the brightness of displays or keyboard lights [114], or noise cancellation technology that measures background noise and filters sound. In the following sections, other sensors are presented in detail, with a focus on positioning and orientation, and a comparison between two compasses is shown.

2.5.1 Location sensors

The *global positioning system* (GPS) is the most popular technique for outdoor positioning, where with at least signals from 4 out of more than 24 satellites the current position can be computed. Selective Availability, an intentional degradation of GPS signals, has be turned off in 2000, and with a clear view to the sky and no signal-obstructing buildings around, an accuracy up to several metres can be provided [18]. To avoid long start-up times required for the scan for satellites, assisted GPS (A-GPS) is a hybrid approach where the handset is assisted by a reference receiver that can predict the satellites available in the current mobile network cell [18]. Differential GPS (D-GPS) is a technique to correct evenly distributed GPS errors emerging for instance from signal spreads in the icono-/troposphere, by measuring a specific point where the exact coordinates are known and applying the difference to all measurements [77]. Other positioning systems rely on the current mobile *network cell*, or measure the signal strengths of networks available in the surrounding, allowing an accuracy of 1-3 metres [108]. *Galileo*, the European version of global navigation satellite system is currently being built by the European Union and European Space Agency. The first launch of this system with intended accuracies of less than a meter is scheduled for late 2010 and the second for early in 2011 [27]. Another approach that is used for car navigation in tunnels where GPS is not available, is to use *3D accelerators and gyroscopes* to compute the position with the help of changes in heading and velocity data (dead-reckoning).

2.5.2 Orientation sensors

Compasses are used to gain direction data. By sensing the polarity of the earth's magnetic field, magnetic north can be identified. This field can be compared to a bar magnet, a dipolar field, with the strongest magnetic field at the North and South Pole (see Figure 2.4). The geomagnetic North Pole is so called because the north end of a compass needle turns towards it, it is actually a south pole. It has to be noted that these geomagnetic poles which lie at the end of the best fitting dipole do not coincide with the geographical poles, but are at the moment about 11.5 degree away from it [31]. Traditional compasses use a magnetic needle which orients towards this magnet field, mod-

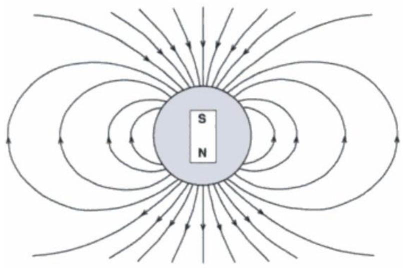


Figure 2.4 – Earth's magnetic field [31]

ern electronic compasses use magnetometers which measure different aspects of this field to get the current direction.

Magnetometers measure magnetic flux densities, common measuring units are *Tesla* and *Gauss*. One application area is the measurement of the earth's magnetic field, that can be used to obtain heading data. Important for using a magnetometer as a compass is not the overall magnetic strength often given as the length of a vector but measuring both the vertical and horizontal magnetic field at a specific position.

An alternative to gain heading data is to use a *series of GPS measures*, but this method has several drawbacks. First, GPS values have only an accuracy of a few metres which means even successively measured values which should lie close together can vary a lot. Moreover, pedestrian navigation systems are often utilised in city centres where the GPS signal is even more disturbed by narrow housing. Small deviations may be reduced by using an approximation like least-squares method. The overall direction is then computed by using the latest x measures to get an average value. However, this results in a new problem, as it takes some time before a new heading is adopted. Another disadvantage of this approach is that it does not work when the user not moving but standing, for example because he wants to reorientate. In this situation the system cannot provide any heading data and the user has to walk into different directions to get information about them. Actively scanning while standing is thus not possible.

2.5.3 Movement sensors

Acceleration forces can be determined with an *accelerometer* and are usually measured in m/s^2. It measures static forces as well as dynamic forces that emerge from active movement. A static acceleration force can be due to gravity that affects non-moving objects and it can be used for example to detect tilt, by looking at which axis is affected.

There are different ways to construct a accelerometer. One is to use piezoelectric sensors which generate a certain voltage when their structure is exposed to accelerative forces which in turn can be measured to get the acceleration value. Other approaches are to quantify the capacitive displacement between two co-located plates as a result of acceleration in a set up where one plate is

stationary and the other can move, or use piezoresistive accelerometers which measure the strain of a spring changing is resistance proportional to its rotation [32].
A *gyroscope* measures how the orientation of the surrounding's orientation changes. The common unit is $degree/second$. A gyroscope consists of a wheel or disk that is rotating like a top. When it is spinning it resists gravity and remains its position which is called conservation of angular momentum [92]. Gyroscopes are for example used in airplanes, where they are mounted inside a gimbal in a way that the contained wheel can hold its alignment independent of its cage's movement. Now the angle can be measured by which the airplane deviates from this quasi invariant installation and parameters like roll can be determined. Using MEMS, gyroscopes can be built using vibrating structures in very small dimensions, see for example the MPU-3000 from InvenSense [127] which combines the measurement structure for all three axes on a single chip and has dimensions of just 4x4x0.9mm or L3G4200D (4x4x1mm) [138] from STMicroelectronics which improves accuracy by conducting the motion measurement along all three axes in a single sensing structure and thus avoids cross-axis interference.

2.5.4 Comparison of mobile phone and external compass

To gain information about the performance of the built-in compass of the mobile phone used for this thesis, and to make sure that the best hardware was used to be able to concentrate on the concept of tactile turn-by-turn navigation which needs accurate and stable heading values, compass tests were performed. Additionally, the tests were conducted with a custom-built bluetooth device to be able to have reference values and as an alternative in case the performance of the built-in compass was not sufficiently accurate.
The Motorola Milestone uses a 3-axis magnetic field sensor, model name AK8973, to compute different orientation values, but it is noticed in the specifications [46] that accuracy can be disturbed for example by the magnetic field of speakers. The same sensor is used in other phones like the Nexus One, which was used in a different project [71] where the internal compass was used for determining the user's direction. The output values can be obtained by an Android application by implementing the interface `SensorEventListener` and its method `onSensorChanged(SensorEvent event)`. Data about the mobile's azimuth (heading relative to magnetic north), pitch (rotation around the x-axis, i.e. the short side of the screen, normally changed when looking at the screen) and roll (rotation around the y-axis, i.e. the long side of the screen) is available. The custom-built bluetooth device contains the OS4000-T, a compass module that uses a Honeywell two-axis AMR sensor for X, Y plane sensing and a Honeywell z-axis AMR sensor with tilt compensation [137]. A bluetooth connection is realised with the bluetooth modem BlueSMiRF Gold [136], which forwards the data it receives over a RS232 connection with the compass module [62].
Different adjustments have been made for this compass module to fit to the experiment's conditions:

- **Sentence output rate** To be able to compare values of the two different compasses and because the internal compass has a maximum output rate of 10 Hz (belonging to the constant `SensorManager.SENSOR\_DELAY\_FASTEST`), the output rate has been set to 10 per second
- **Declination angle input for true north** Since there is no possibility to set this declination angle for the internal compass, this value has been set to 0 for the comparison tests.
- **Filter heading, roll and pitch** To average output values, this value can be set. For the tests, no filtering is applied to the output.
- **Scale magnetic field output** To get more precise results, the local horizontal field strength of the earth's magnetic field is calibrated to local values, which can be looked up on the

website of the NOAA [130]. For the area of Lancaster university this value corresponds to 18,094.4nT or 180.094 mG.

- **Decimation filter for AD** This setting concerns the noise filter and is left at the default value of 3 which means there is some filtering.

- **Degauss and offset rate** The rate how often the compass degausses itself is set to 5 which means in combination with the sentence output rate of 10 that the compass executes this operation twice in a second which is, according to the compass's manual, enough to keep the lag low when moving the compass quickly.

The following tests were made with both compasses simultaneously to have a direct comparison. For both compasses the raw output without averaging data was used. A K'NEX Ferris wheel kit was rebuilt to create a horizontal rotation at a fixed speed, to see how fast the output adapts to a new position. It was chosen because all parts of the kit are made of plastic to avoid interferences with the compasses, and a motor delivering sufficient power was also included. Since the external compass was lighter than the mobile phone its side was additionally loaded with a roll of tape to allow a smooth angular movement. For the test of performances with applied tilt angles, ramps made of cardboard were used. Figure 2.5 shows the complete setup. Before each test, the two

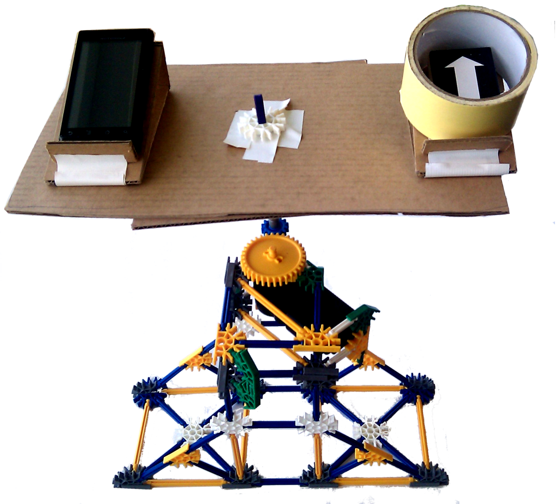


Figure 2.5 – Compass test: Setup for tilt angle of 30°

compasses were calibrated and positioned on the disc. After checking that the installation is properly balanced, the logging application was started and afterwards the data from run 2-4 out of five were used to avoid disturbance caused by powering up the motor or putting the compasses on the disk. The different tests conducted were the change of heading output when rotating with 0°, 30° and 45° tilt angles. Heading data of the built-in as well as of the external compass was compared with the actual, linearly changing, heading data which was computed from the start and end value of one rotation period.

While working with the compass built into the Motorola Milestone, it often appeared that it suddenly provided values deviating more than 30° from those shown before and thus it had to be recalibrated. There is no official description of how to do this, the most common way to calibrate the sensors of other mobile phones is to move it in a figure-8 type pattern several times. This turned out to work in most cases, however sometimes it had to be repeated several times, once the phone had to be turn off and on again.

Figure 2.6 shows the results for both compasses when turning them on the Ferris wheel with a tilt angle of 0°, 30° and 45°. Additionally to the heading outputs of the two compasses, a ideal line is drawn in, however, since the output values are very accurate, these lines overlap strongly. It can be seen that at least for a slow movement (a whole rotation took about 30 seconds), both compasses perform very good. Analysing the test data more closely it became apparent that the motor to

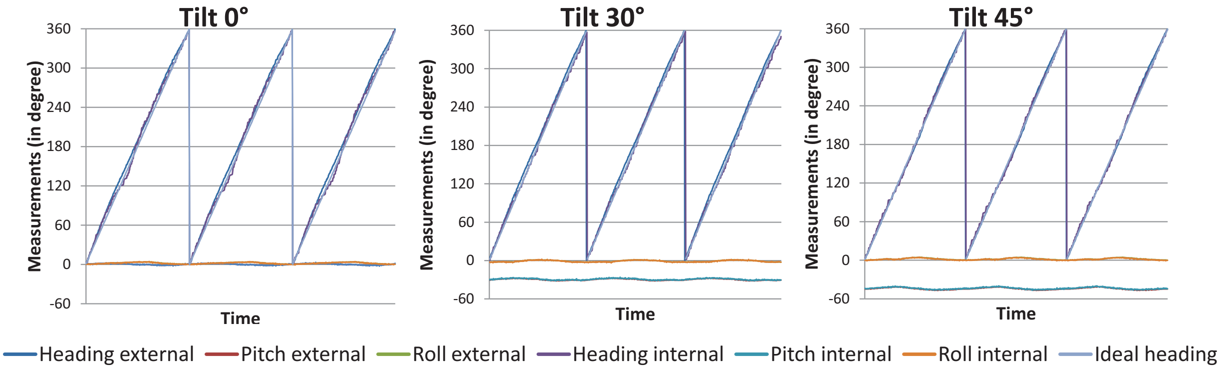


Figure 2.6 – Compass test: Heading results of both compasses for different tilt angles

create the rotary motion had an influence on the measurement. When looking at the differences between ideal linear heading and compass outputs during three runs one can see that there are regular peaks in the curve indicating that always when a compass came to the point of rotation where it is closest to the motor, compass sensing was influenced. For example, in the series "Tilt 0°" (see Figure 2.7), the difference for the internal compass reaches a peak at about 150° which is exactly the position where the compass was moving above the motor.

Nevertheless, there are periods where none of the compasses is moving over the motor, and look-

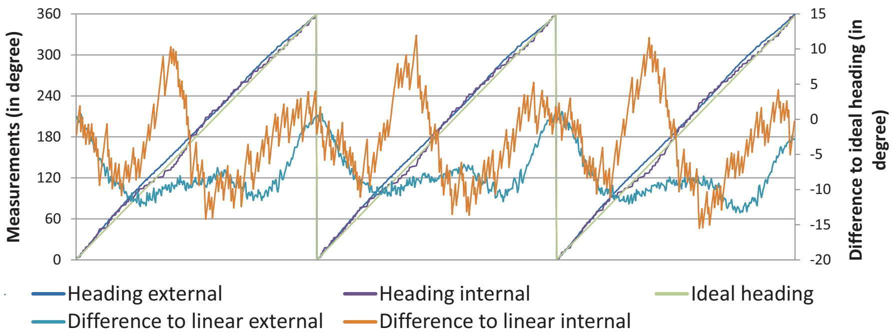


Figure 2.7 – Compass test: Measurement errors for both compasses with no tilt

ing closer at one of those reveals that the results given by the external compass are a lot smoother than those measured by the internal one. The internal measurements form a clearly jagged curve where often a series of 6-7 of measurements almost give the same value, as can be seen in Figure 2.8. Over six measurements (corresponds to 0.5 seconds) only 1.5° of progress are indicated. This is only 22.5% of 12.3° which is the average progress over this period.

Tests were also conducted where a call to a service line was placed on the mobile phone and therefore speakers were active, but even with speech output which was said to possibly affect the

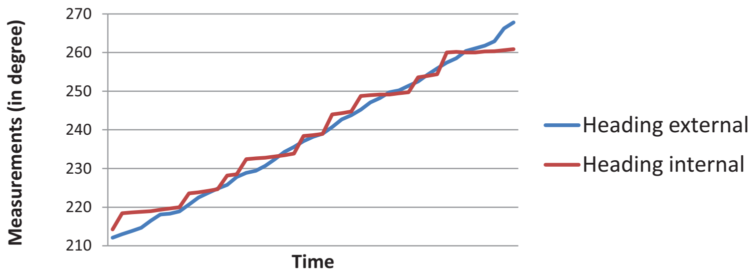


Figure 2.8 – Compass test: Close look at the measurements of both compasses

compass results, the performances did not differ significantly. The tilt compensation of the external compass did not outperform the internal one, even not in further, less controlled, informal tests, where both compasses were places on a wooden plate to ensure equal orientation and then carried around a winding course.

However, the later decision to use the C2 tactor for vibrational feedback (see Chapter 4.1) made the usage of the internal compass impossible. The tactor is a strong magnet, thus attaching it to the back of the phone disturbs the magnetic measurements and thereby makes the heading values unusable.

3 The sense of touch

Tactile displays can be used as an alternative form for visualising information instead of visually or auditory [64]. This chapter concentrates on how to use tactile feedback for stationary and mobile devices. First, an introduction into human capabilities to perceive stimuli presented to the skin is given, and the multiple resource theory and its impact on the perception of several stimuli at one time is discussed. Characteristics, potential and problems concerning this additional channel is given. Furthermore, existing research using vibrational feedback is described.

3.1 Human perception

The human sense of touch can provide a huge range of information about the environment [17]. Besides the perception of different kinds of pressure by mechanoreceptor cell, heat and cold as well as pain are recognised by cells called thermoreceptors or nocireceptors integrated in the skin. Furthermore, proprioceptors are used to control the status of muscles and joints. This supports the kinaesthetic sense which is used to be aware of the positions and movements of the limbs. This is applied for example in force feedback devices like joysticks, where the position and the forces affecting the hand that controls the device give the player rich information about the current interaction.
In the following, the main attention lies on the mechanorecptor cells. Brewster et al. [9] call the resulting sensations cutaneous perception since it is caused by the direct contact between tactile display and skin surface. Skin indentation, vibration and skin stretch are the techniques most often used to create the tactile stimuli.
The class of mechanoreceptors can be split into four receptor systems shown in Figure 3.1: Pacinian corpuscles mainly respond to temporal changes in skin deformation and interpret move-

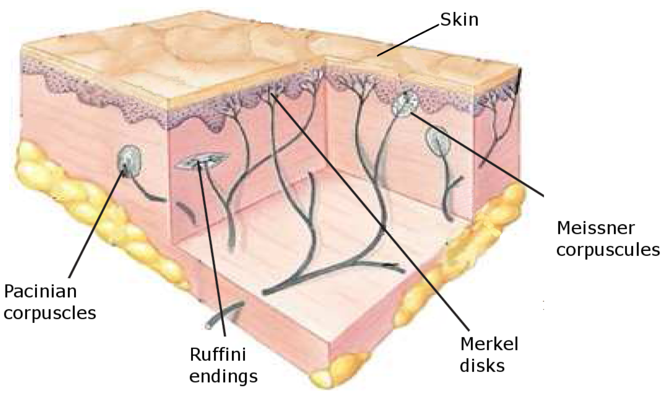


Figure 3.1 – Anatomy of the human skin (adapted from [16])

ments on the skin in terms of acceleration of stimuli, while Ruffini endings (or cylinders [61]) are responsible to translate skins stretches into emotions like motion of static force. Meissner corpuscles are used to detect velocity or flutter when something is moving along the skin. This is for instance used as grip control and helps to notice when something is slipping from one's hand. Finally, Merkel disks respond to skin curvature, like feeling the raised surface of Braille letters used to present text for visually impaired people.
All of these contribute to the perception of vibrations, but Pacinian corpuscles are most sensitive. The perception is dependent on the frequency of presented stimuli, where the best sensitivity is given at 250Hz. A displacement of less than one μm can then be perceived. This mechanical displacement then has to be converted into neural action potentials, which is call mechanotransduction [61]. The density of receptor cells varies across body. The highest concentration can be

found in fingers tips [9], the part of the body which is naturally used for exploration and manipulation [38], so these are the regions of the body that is most sensible for the perception of tactile feedback. However, Gallace concludes from his analysis of vibrotactile interfaces that it is conceivable that training can reduce the differences between fingertips and other parts of the body which are normally not used for this, and then additional regions such as wrists, arms, or waist could be used to convey information via vibrations [33]. Especially for older and (visually) impaired people, vibrations can serve as an alternative perception channel to others that are degraded [9]. The perception via tactile interfaces seems to be less reduced when growing older than other channels [33]. Visually impaired show better performances in a version of Guitar Hero enhanced with vibrational feedback, most likely due to regular training of their cutaneous perception [118]. However, aging effects can lead to a reduced perceptual capacity compared to younger people [9]. By adjusting the strength of vibrations to the same subjective level, these differences can be balanced [102]. A possible problem with vibrations can be masking effects that occur when different vibrations are close together in space and time [61]. Moreover, the tactile analogue of the visual "change blindness" exists [33], so users can fail to detect a positional change of two successively presented stimuli, when a distracter is presented between the two to-be-compared tactile patterns.

3.2 Using an additional perceptual channel

The motivation to use tactile feedback for the transmission of navigation information is that the visual channel is needed for other tasks, such as watching the surrounding and taking care of the traffic. In contrast, resources of the tactile channel often remain unused. According to the multiple resource theory [109], different perception channels can be used simultaneously, and adding a new channel does not cause the degradation of an existing one. A user should therefore be able to walk along a street and use the visual channel for scanning his environment, while navigation instructions are given over a non-visual channel, such as vibrating in a specific way [39].

The original model of 1984 [109] contains three axes, along which resources can be shared,

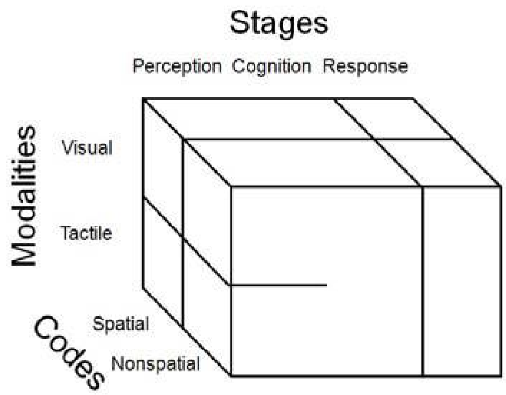


Figure 3.2 – Multiple resource model: structure of processing resources for a visual/tactile task set [28]

namely the *stage* of processing, the *modality* that is used and if the *code* of the perceived information is spatial or not. The model has been developed further by Ferris in 2010 [28] who transferred the model from visual/audio to visual/tactile (see Figure 3.2). He examined the influence on processing and interpretation of tactile information when both visual and tactile information is coded as spatial pattern. He found that a degradation of performance can be expected, because not only in the perception stage the channel must be different, but the coding of information has to differ, too, to not collide during cognition stage. For the navigation task with tactile feedback, the visual channel is used to watch the environment, while vibrations give cues about how to move in there, so both refer to spatial knowledge. However, the collision during processing can be minimised by designing the signals as intuitive as possible so that the cognitive load for interpreting the input is reduced.

Crossmodality In contrast to multimodality, where information is presented over different modalities [17], crossmodality describes the situation where different modalities present the same information. An example would be when a button on a touchscreen surface is pressed and not only the appearance of the button changes but also tactile feedback is given [39]. But still, the maximum capacity per channel remains the same, so if modalities are used that share the same processing resources, an overall worse result can emerge than when using only one modality.
Van Erp and van Veen compared visual against tactile and multimodal presentations of navigation symbols in a virtual driving environment [25] [23]. Visual feedback was given with arrows and alphanumerically indications of distance, tactile feedback was realised with overall eight vibrators built into a car seat, four under each leg. Direction was presented by vibrating on the respective side, while the rhythm was changed to indicate distance. They found that the mental effort as well as the reaction time of a peripheral detection task could be reduced when replacing the visual by a tactile or multimodal interface, with the lowest reaction times achieved with multimodal displayed instructions and lowest mental effort results with tactile-only. Moreover, the performances of the alternative presentations were insensitive to an increased workload level, in contrast to a raise of reaction time in the visual condition of 10%. They state that even clearer results can be expected with more training and a further increase of workload, however, they warn that with more complex information, the intuitiveness of signals could get lost and an overload of processing resources could cause an overall decline of performance.
Gallace et al. [34] examined the differences in the numerosity judgement of stimuli that where either presented unimodal or bimodal (vibrotactile and visual). The bimodal performance was not predictable by the unimodal results, and so they highlight the importance of testing tactile feedback in combination with a realistic visual workload. Concluding a survey of recent studies of multisensory processing, they suggest to improve the performance by using different modalities redundantly [33]. As mentioned before, the multimodal representation of instructions can improve performance over tactile-only interfaces, however, as soon as visual feedback is given additionally, it has been observed by Rydström et al. that it can possibly dominate the perception and tactile feedback is neglected [81]. Regarding the navigation task, a realisation could therefore be to offer a map-based application as an overview to get a mental image of the way, but to do the turn-by-turn instructing with vibrotactile feedback.
Crossmodal representations can be used to adapt feedback to the current context. Modalities with shared dimensions, like rhythm and tempo for auditory and tactile feedback [9], also called *amodal* [13], can be combined and depending on the background noise or vibration level, either the one or the other performs better [42]. The ease of switching between modalities has been shown by Hoggan and Brewster [39]. Participants were either trained the audio or tactile representation of information, and then used use the respective other coding. Performances were almost as good as in the control condition, where the same modality was trained and tested. It can therefore be useful to learn codings via an easy accessible modality, for example with a visual representation, and then transferring this knowledge to another modality like tactile which is then used.

3.3 Definition

A popular definition for tactile feedback was brought up by Brewster and Brown [7]. They define a tactile presentation for a certain kind of information as a tacton. Visual information can be compressed in space to an icon, speech can be presented as a concise earcon. In a similar way, tactile information like Braille encoded text, or iconic and pictorial data [9] can be represented

as a specific vibration pattern. This can on the one hand save space, when instead of a sheet of embossed Braille characters only a small vibrator is needed, on the other hand it also saves time to only perceive a vibration pattern instead of successively scanning the information. MacLean and Enriquez call tactile representations haptic icons [57] or hapticons [20], while van Erp uses the term vibrocon [25]. To expand the coding of information, tactile feedback can be structured in different ways, like compounding different short vibrational pulses to more complex tactons, or organising them hierarchical by adding additional parameters for every layer of extra information [7]. Regarding crossmodal representations, vibrations can be combined with visual and audio feedback, and therefore enhance both icons and earcons because they operate temporally and spatially [7].
The device which is used to create a vibrotactile sensation [56], is in the following interchangeably called *vibrator* and *tactor*. While vibrator is the more common term used when talking generally for instance about mobile phone enhanced feedback, tactor is often used in technical descriptions.

3.4 Potential of tactile feedback

So far, tactile feedback is mostly used additionally to enhance existing visual or auditory information. However, it can have different advantages over other representations. Thinking of the most popular usage, notifications in mobile phones, vibrations serve as a pleasant, discrete indication for a call or alarm in a quiet environment, but are still sensible in a noisy context [12] [78]. An important aspect is therefore that it can be used to privatise a large range of different information that are to be displayed [9]. Listening to vibrations stored in the trouser pocket frees the user from the need to look at the screen [76] and allows to have the hands free for other tasks [37] such as carrying baggage [102]. Tactile feedback is already included in most mobile phones and other mobile devices, so no further equipment is needed [37], and vibrations can easily be integrated. In this way, familiar devices can be enhanced without lowering the acceptance rate and allowing to seamlessly switch from one kind of feedback to the other [37].

Complex information It is possible to present more than the simple 1-bit "your phone is ringing" message [25] with vibrations. Brown et al. [11] showed the potential of tactons by testing the transmission of 3-dimensional information adjusting 3 different parameters. Each of these parameters had 3 different levels, resulting in 27 possible messages. In a first run, they achieved a recognition rate of complete tactons of 48%, and after reducing the most critical parameter (roughness) to 2 levels, even 80% of messages (of now 18 different) were identified correctly. Furthermore, conveying progress information of a download task by creating a rotational movement over three tactors with increasing speed has been successfully applied by Hoggan [38]. Participants reacted faster to the end of the download, and at the same time made less errors in a simultaneously performed text entry task.

Unobtrusiveness and intuition As discussed before, tactile feedback is perceived over a separate perception channel than visual and auditory information. It does not consume capacity for seeing and hearing, and at the same time, it is always ready [25], even at night or with fog [103]. However, an exception are situations, where a high overall vibration level is present such as in cars [82] or underground trains [42]. In this case, a different type of feedback should be chosen. Tactile feedback can be intuitive when the kind of information displayed is appropriate [25]. Bosman compared the usage of visual signs and guidance with vibrations given on either the left or right wrist, and found that the perception of information is less delayed using tactile feedback, even at non trivial decisions. A more immediate reaction could be provoked, without the signals being regarded as disruptive [4]. Participants even pointed out that they got a feeling to be on the right way instead of thinking about where to go. Heuten et al., who tested the perception of tactile feedback given by a tactile belt, also found that stimuli can be sensed quickly and exactly. In their case, the feedback was intuitive and did not cause a high cognitive effort to decode the signals, as users had an egocentric view on the presented information and only needed to map the horizontal location on the belt to the direction they were heading to [37].

Memorability Tactile signals have the potential to be memorable. Enriquez and MacLean [19] tested the memorability of different tactile signals without any interim reinforcement. They also examined if there is an effect whether arbitrary meanings are assigned to the signals or the participants can choose their own tactile representations to a set of given meanings. The two sets containing 2x10 meanings were taken from a navigation system (e.g. "Go right" or "Faster") and an audio system (e. g. "Volume" or "Tuner"). The conducted study was split in two parts: one to learn the meanings, and a second part which took part two weeks after learning. It revealed that there is no significant difference between the two association modes and that recall rates are surprisingly high with an average of 86%. An interesting fact is that participants did not think they could recall meanings before they performed the second part of the study. Comments show that even if meanings were randomly assigned (which was not explicitly declared) participants often built up their own metaphors.
Another study that shows how well tactons can be remembered was conducted by Hoggan et al. [40]. They designed a device called CrossTrainer providing multimodal feedback for mobile gaming. Besides the gaming feedback, different three dimensional tactons and earcons were presented during playing, indicating incoming calls, emails and texts with different urgencies and belonging to different contexts. These were introduced only in a short training at the beginning and participants had to recall their meanings during an eight day study. After the training already 75% of tactons and earcons were identified, and after another three runs during the field study people were able to identify 100% of tactons, this performance level was held until the end of the study.

Context dependent preference The main test of the same study [40] by Hoggan et al. was about when participants would choose to use which kind of feedback for gaming support, indicating for example where on the screen the user has to input his answer and how many time remains to answer the current question. It turned out that tactile feedback was clearly preferred while playing at home, at work and at restaurants whereas audio was chosen more often when the vibration level exceeded 8.1g, for example while commuting, because tactile feedback could not be sensed clearly. In contrast, a noise level of > 91dB causes a preference for the tactile modality. "Social acceptability" turned out to be an important factor because participants did not want to disturb others with beeping sound so they often chose tactile feedback when other people were around. The task for which the feedback was given also influenced their preference, audio was seen as better suited for small widgets such as buttons or when a large amount of feedback was given such as when typing in text. Tactile sensations were preferred for larger and more infrequent widgets such as progress bars. After testing each modality for two days, participants were asked to play another two days, choosing the modality they preferred. In 82% of cases, tactile feedback was chosen, the rest decided in favour of audio feedback. The visual only representation was never used. This shows the potential of enhanced feedback while interacting with mobile touchscreens.

3.5 Rich tactile interfaces

The next section gives an overview over different research projects using tactile feedback (see Table 3.1 for an overview).
Yatani and Truong [117] developed SemFeel, a mobile phone enhanced with five vibration motors. A special sleeve was built to avoid a gap between hand and device for clearer sensation. They tested different patterns creating positional and linear or circular flow sensations. Ten out of eleven patterns could be recognised in over 80% of cases, only circular movements (counter-/

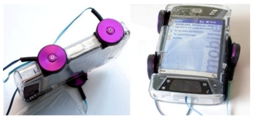
Author	Interface	Experimental design
Yatani and Truong (2009) [117]	 Five vibrators attached to back of mobile, positional, linear, circular patterns; no, single and multiple tactile feedback	Pretest: Differentiation of patterns. 12 participants, compare performances with no, single and multiple tactile feedback for number input task
Strachan et al. (2009) [96]	C2, tactile feedback based on touchscreen gesture or turning of device, dynamically adapting the velocity of input	-
Hoggan et al. (2007) [38]	4xC2: Tactons using location and rhythm; sensation of circulation (3 tactors)  to simulate progress bar, rhythm for progress, 4th tactor to indicate keyboard slips	Pretest: Differentiation of patterns. Main test: 8 participants, compare performance with no or tactile feedback for text input and tactile or visual feedback for progress indication
Williamson et al. (2007) [110]	Built in (iPaq) and additional vibrator: changing intensity for temporal changes of different kinds of information	-
Sahami et al. (2008) [83]	 6 standard vibrators for mobile devices, directional movements by successively activating vibrators	13 participants, differentiation of positional and directional movements
Chang et al. (2009) [15]	Glove-like device with 3 vibrators for each finger	Observations of emerging patterns during usage
Lee and Starner (2010) [53]	3 vibrators in wrist-worn device, indicating different alerts, circular sensation with different starting points	Pretest: 12 participants, differentiation of patterns. Main test: 16 participants, compare complex tactile with a combination of simple tactile and visual feedback
Kohli et al. (2006) [47]	 15 vibrators in three rings on right upper arm, speed (duration between single vibrations, may overlap) and motion (no meaning)	10 participants, investigate recognition of different vibrational parameters
Rydström (2009) [81]	ALPS Haptic Commander (haptic rotary knob), amount and strength of peaks (for different textures, to indicate different menu items, meaning learned in advance)	40 participants, compare selection performance with visual, haptic or combined feedback
Chan et al. (2008) [14]	 Logitech iFeel mice, vibration patterns for a turn taking protocol	Pretest: 12 participants, identification of tactons. Main test: 16 participants, shared cursor application, either visual or haptic feedback

Table 3.1 – Rich tactile interfaces

clockwise) were mixed up occasionally. A second study was conducted comparing different kinds of feedback for number input. Either no tactile, single vibrations, or complex vibrations incorporating the different vibrators of SemFeel were applied. The more advanced feedback was given, the more error rates decreased, but at the same time, performance times increased.
OverView is a system by Strachan et al. [96]. They used vibrational feedback to visualise curve data, like the trend of stocks and shares, as a continuous vibration with raised intensity when peaks in the data occur. They built a complex dynamic model where the rotational movement of a phone or the position of an onscreen slider are used for input, and the output is computed taking into account varying input speeds.
Hoggan et al. [38] developed a mobile multi-actuator tactile display, where four C2 tactors were attached to a PDA to make use of the entire hand's surface. Used positions were upper and lower thumb, and the tip of index and ring finger. Testing tactons using location and rhythms, a 100% recognition rate of location could be achieved. Rhythms containing 2 pulses were easily recognised, rhythms with 4 or 6 pulses were mixed up in 16% of cases. A second prototype application made use of the principle of sensory saltation. With three circular mounted tactors, a rotational movement can be simulated by activating each of them three times. Instead of being perceived isolated, an impressions of a continuous vibrations is generated. With this motion, a download progress was indicated, getting faster when more progressed. A comparison with a visual progress bar showed that the response time to the end of the download was significantly shorter using vibrations for indication, even if combined with a second task using tactile feedback.
Williamson et al. [110] developed Shoogle, where two vibrators, the built-in of an iPaq and an external one, were used to create vibrations. They introduces the metaphor of a box with balls inside the mobile phone representing incoming messages. Those can be shaken to sense how many and how long messages have come in. No real spatial distribution of vibrations was realised, but with techniques like rapid or slightly in- and decreasing vibrations, or summing up multiple short pulses, and additionally playing different kinds of sound, the feedback was easy to understand.
A mobile phone enhanced with six vibrators was used by Sahami et al. [83]. Vibrators were located at the four corners and two more at the centre, to have them maximally placed from each other. A first test showed how good different locations could be perceived. Left-right, top-down and the four corners could be discriminated with a recognition rate of about 75%, whereas actuators in the middle could not create a clear impression of location which resulted in an overall recognition rate of single vibrators of 36%. A second test investigated the differentiation of motional patterns (circular, top-down or right-left). Circular motions (always 1 vibrator activated) achieved the best result with 82% recognition rate, top-down (2-2-2) 51% and right-left (3-3) 68%, showing that the number of activated vibrators does not influence the perception.
Chang et al. [15] enhanced speech during a call with haptic impressions. Pressure given on the one side is transformed into vibration on the other side. With the finger tip, tactile feedback is created, a vibrator at the middle of the finger shows how own given feedback feels, and one near the palm presents vibrations as the dialogue partner has given it. A user study showed, those vibrations are mainly used to emphasise what is said. Moreover, mimicry of signals the other produced (as a yes-I'm-listening signal) was observed, and the haptic feedback was used for turn-taking, where a series of presses was given before beginning to speak.
Lee and Starner [53] used a wrist-worn tactile display called BuzzWear to present circular movements, differing in starting point, direction, intensity and number of pulses per location. Strong learning effects over sessions show the quick adoption to before unfamiliar feedback, and overall recognition rates were very high with >90%. Three pattern, distinct in the starting point, were chosen for a second study. Three different signals were either given via BuzzWear, or visually on a mobile phone with a simple tactile notification. They could show that an increasing difficulty of a secondary visual distraction task had less influence on reaction times with the wrist device. Physical workload was observed for the mobile phone because of the extra effort to look at the screen, while mental workload was slightly increased using BuzzWear as a mapping between patterns

(circular) to meanings (linear keypad layout to input what was perceived) had to be performed.
Abstract tactile patterns using speed and motion pattern were investigated by Kohli et al. [47]. They built a device containing three rings, each including 5 tactors, to be worn on the upper arm and first tried to find the just noticeable difference (JND) for the time between the start of vibrations. They found that strong overlapping of one third leads to the impression of a fast movement, while delays of about twice the vibration duration led to the impression of a slow movement. In a second study, independent variables were speed (3 levels) and motion (clockwise, counter clockwise, up, down). Motions were easy to distinguish, however, circulations were only distinct at the start, not when rotating several times. Results show that especially the extreme speeds were easy to perceive, suggesting to only use two different levels.
Rydström et al. [81] examined different feedback types for an in-car menu selection task. Items were either indicated visual, visual enhanced with simple or complex haptic, or haptic feedback only. The menu item order differed in every run, therefore haptic feedback had the disadvantage that each item had to be scanned sequentially, resulting in fewer accomplished tasks. However, workload levels were equal. Eye movement data was analysed in terms of percent road centre (a circle with a radius of 10°). Results show that in the haptic only condition, eyes were kept on the street during selection, whereas values were significantly lower for the other conditions compared to baseline driving, indicating that as soon as visual feedback is given, attention is shifted towards it. Ryu et al. [82] also tested in-car menu selections with a vibrotactile knob, during a driving-like primary task. Items were identified via patterns differing in intensity, duration and rhythm, without any visual feedback. Between 3 and 6 menu items were presented, however, the number of items did not have an influence on the results. Results show that correct items could easily be chosen (97%), and the performances in the primary task were near perfect, indicating that selecting did not interfere with driving.
Chan et al. [14] investigated the problem of turn-taking of the cursor in a collaborative environment. Their goal was to increase the turnover rate and equitability of time-in control. Different haptic icons had been developed, providing metaphors to easily remember associated meanings and using families of signals, relating to the states *in control*, *state change* (gain or lose control), *wait for control*, or *observing* (no feedback). A first study revealed too subtle signals, but also showed good identification rates of 95% and a mean detection time of 4 seconds. In a second study, users had to solve a collaborative task, using either haptic, visual or combined feedback. Vibrations were preferred for acquiring control, while visual feedback was preferred for displaying the current state like showing who is in control at the moment, especially because no name was presented in haptic mode, and there were times where no feedback was given (*observing*). Overall, the combined interface was most preferred.

3.6 Tactile feedback for an orientation task

This chapter will give an introduction into existing research using tactile feedback for an orientation task like navigation or locating points of interest in the environment. It is split into different sections depending on how complex the used devices are.

3.6.1 Using the built-in vibrator of a mobile phone

This section discusses work that uses the vibrational feedback being available on standard mobile phones. Rukzio et al. [80] used vibrations in addition to public displays, where successively all possible directions where displayed. A vibration was used to identify the current direction as the correct one for a single user. In the following, systems are represented were vibrations are the only modality used (see Table 3.2).

Lin et al. [55] use different rhythms varying in pulse number and duration to indicate a direction (left or right) or the end of a route. Distance to the next crossing is realised by playing the

Author	Interface	Experimental design
Lin et al. (2008) [55]	Rhythm/melody for direction, tempo for distance	Recognition test and field test of concept
Pielot et al. (2010) [71]	Duration of signals and pauses/rhythms for direction and distance	Comparison with map in an outdoor navigation task
Robinson et al. (2009) [75]	SHAKE hardware pack including sensors and haptic feedback, vibrating when scanning a specific direction	Initial study about recognition rates and walking speed
Williamson et al. (2010) [111],		Field study of indicating a common meeting point for a group of people
Robinson et al. [76]		Field study where navigation information is given by vibrating in the area of possible ways

Table 3.2 – Existing research using tactile feedback for a navigation task: using the built-in vibrator of a mobile phone

rhythms with different tempos (medium/adagio for "at the next block", fast/allegro for "now"). A first laboratory study was conducted where participants were presented the tactons repeated four times and then told a moderator which direction and distance had been indicated. Direction was correctly recognised in 100%, distance showed a recognition rate of 99%. In a second study, four participants who were already part of the first study, tested the system outside on campus of Tatung University. A wizard of Oz technique was used to realise the timing of vibrations. All signals were recognised correctly, even tempo/distance. This was easier in the real setting than in the first study, because medium tempo is always coming before fast, at least in a study setting where effects like GPS inaccuracy do not cause missed signals, whereas indoors signals were randomised. Participants could walk with their normal walking speed. However, task load has not been measured to show if signals were intuitive or unobtrusive, and no comparison with an established navigation system has been conducted.

Pielot et al. [71] developed the PocketNavigator, a compass-like system where the user is always guided to the next waypoint of his route. For this purpose, respective vibration patterns are played. The set of tactons used is called TwoPulse, so a set of two vibrational pulses indicates the direction. In contrast to the previous system, constant feedback is given. As long as the two pulses are short, the user is going straight towards the next point to turn. Assuming that a slight left turn is required to reach the next point, the first vibration is longer, and the longer it gets the more one would have to turn around. A right turn is indicated by an extended second vibration. An exception is the special signal for an angle of 180° (+/-22.5°) or "turn around". It stands out as it contains three short pulses and since it breaks with the rhythm of two pulses, it is very obtrusive. Additionally, distance is encoded as the duration of the pause between two tactons, which becomes shorter the closer the next waypoint comes. The guidance always refers to the current position and heading of the user, and the feedback is adapted according to the user's behaviour. A user study was conducted where participants had to reach three destinations in a city forest, with either a map where the destination and their current position, the tactile compass only, or both. Additionally, they had to spot benches spread over the area. In this study, the tactile feedback only showed the overall direction to the destination instead of single waypoints, and distance was left out. Results show that the destination could be reached with the PocketNavigator, and there are less interactions with the device than in the visual or combined mode. However, no significant difference in spotted benches or in the task completion time could be shown, indicating at least no disadvantages compared to the visual guide.

Williamson and Robinson used a Sensing Hardware for Kinaesthetic Expression (SHAKE) SK6 sensor pack in several projects integrating context sensing hardware like accelerometers and providing vibrotactile feedback similar to a mobile phone. For instance, Robinson et al. [75] developed a low interaction cost approach to discover geo-tagged information, where a person can search the near environment for points of interest by feeling vibrotactile feedback when the focus is moved towards a target, similar to the city guide system of Takeutchi and Sugimoto [97], who compare their interface that beeps when held in a direction where recommended shops lie, with a metal detector, and plan, after a first user study, to replace the audio beeps with tactile feedback. The concept of actively scanning helps to minimise mapping costs required when information is presented visually on a screen, and allow a direct interaction with the environment. Robinson et al. tested the approach in an indoor environment where participants had to walk a slalom course while identifying targets, either with the tactile or a visual interface. Using haptic feedback, less errors were made and participants reported less time pressure when listening to vibrations. Since haptic feedback was given dynamically, the searching behaviour was more exploratory and therefore slower, resulting in a slightly slower overall walking speed. Another application was developed by Williamson et al. [111], where the device was used to sense for an overall direction. Several people, who want to meet up, use their devices to scan for the central point between them, and are guided by a pulsing vibration given when the device is held in the correct direction. Results show that simultaneously walking and scanning is no problem most of the time, only sometimes participants stopped to scan for the direction. The overall concept of not presenting concrete routing instructions, but to present an overall direction, was taken well, and participants were able to find their own ways. A similar approach was realised by Robinson et al. [76]. Haptic feedback was used to provide the overall direction to a destination. Users can scan their surrounding and if they point to a range of 60° around the destination, vibrational feedback is given. Additionally, they tested a dynamic approach where the range of 60° is broadened to up to 120° if there are more ways that lead to the destination. The advantage of not having turn-by-turn instructions is that it is not necessary to follow concrete instructions but to move more freely and take into account the visible environment, where different kind of paths may be available or prior knowledge about the area may be available. In a field study, all participants reached the indicated destination, suggesting that the feedback provides enough information. With the dynamic approach, participants acted more exploratory and were able to use prior knowledge about the area and the visible path layout more effectively, resulting in faster walking speed and the choice of shorter ways.

3.6.2 Using separate vibrators for left and right

This section presents research with custom-built devices where the direction is basically indicated by vibrating either on the left or right side of the body, an idea that was already mentioned 1997 by Tan and Pentland [99]. A summary is given in Table 3.3.

GentleGuide, a device developed by Bosman et al. [4] for an indoor navigation task, contains two vibrators included in boxes worn around wrists. A short (0.7 seconds) vibration on a wrist means to turn towards this direction, a short vibration on both wrists means the destination has been reached, whereas a long (1.5 seconds) vibration on both wrists indicates walking in the wrong direction. A study was conducted where the tactile feedback was compared with wayfinding by means of signs. The prototype was not fully functional, so feedback was controlled remotely. Providing turning directions with vibrations outperformed following signposts in terms of walking speed and subjective preference. The feedback was said to be intuitive and easy to learn. However, the acquisition of spatial knowledge was better using signs where users had to find the way on their own.

Ghiani et al. [35] designed a module to be used for visually impaired people during a museum visit. It is attached to a PDA and guides people from one artwork to the next, while descriptions are given as audio messages. Two vibrators are attached to thumb and index finger, where the

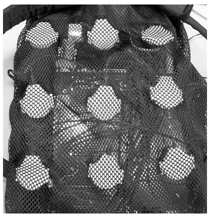
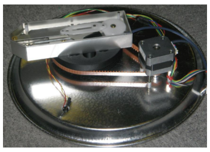
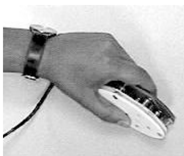
Author	Interface		Experimental design
Bosman et al. (2003) [4]		Two boxes worn on wrists, location (left/right/both) and duration for direction	Comparison with finding the way with signposts
Ghiani et al. (2008)		Vibrators on thumb and fore-finger of one hand, location, duration and frequency for direction, rhythm for distance	Field test with blind participants
Poppinga et al. (2009) [72]		Vibrators attached to handle-bar, location and strength for direction, duration for type of waypoint	Field test of concept
Ross and Blasch (2000) [78]		Shoulder tapping interface (vibrators on shoulders and neck area), location and number of taps for direction	Comparison with a spatial audio and a speech interface in a street-crossing task, 15 participants with different levels of blindness
Vainio (2009) [104] [105]		Real tapping on shoulders and in between, different timing for indications	Comparison with overview map as well as visual and auditory instructions
Amemiya (2007) [1]		Two-dimensional force display (creation of directional pushing or pulling)	First investigation of functionality and intuitiveness without training
Amemiya (2009) [2]		Pseudo-attraction force display (creation of directional pushing or pulling)	Comparison of tactile feedback only and the combination with auditory cues
Sokoler (2002) [93]		TactGuide, raising pins under thumb on left or right show direction	Treasure hunt study

Table 3.3 – Existing research using tactile feedback for a navigation task: using separate vibrators for left and one right

messages "Rotate left/right/left a bit/right a bit" are given as vibrations at the respective side, long and strong for more than 90°, or short and weak for less than 90°. They compared the feedback with spoken versions of the messages. Additionally, distance was encoded in both versions with beeping sounds repeated more often the closer the artwork was located. Users stated a preference for vocal messages in terms of confidence, mainly because they were more familiar with this kind of feedback. This would probably become better with more experience, however, it showed that the vibrations were not immediately intuitive and easy to use.
A different application area was examined by Poppinga et al. [72]. They attached vibrators to the

left and right of handlebars of bicycles. Intensities of directions were interpolated to be able to communicate more than pure left and right. Duration was used to differentiate between different types of indications; a long duration showed the overall direction to a destination, short duration points of interest on the way. In a pilot outdoor study, participants were ask to cycle to a destination using vibrations or alternatively a visual display of the directions. Five out of six mainly used the vibrations. Feedback contained positive aspects like an increased environment awareness and the reduced need to explicitly gain orientation information, as feedback is given constantly, and every participant could reach the destination without any additional guidance. However, especially the indication of POIs was a problem as the difference of durations was not intrusive enough.

The first works were based on two-point-interfaces, whereas the following research projects use a third point in the middle of left and right.
Ross and Blasch [78] used a device to imitate shoulder-tapping for a street-crossing task helping visually impaired people to reach the other side in a straight line, minimising the time spent on the street. A tap was realised as a vibration either on one of the shoulders or on the neck where vibrators were attached within a vest worn by the participants. Confirmation for a correct heading was given as two taps in the middle, a slight deviation by a tap on the respective shoulder and the middle, and a deviation of more than 7.5° by a shoulder-only tap. The interface was tested in comparison with a speech interface, giving hints every two seconds in clock-directions ("two o'clock" ... "one o'clock" ... etc), and a sonic interface indicating the direct line with a spatial tone. Performances and preferences varied according to the degree of impairment, but overall, tapping and spatial sound beat the speech interface. Participants highlighted the advantage of tactile feedback that it does not imply wearing headphones, and is still perceivable when sound is covered by street noise. Moreover, it created a natural and easy to adapt feeling for the right direction.
A similar concept of tapping was used by Vainio [104] [105], who used real shoulder tapping in her user studies. Two different concepts were developed regarding the timing to present navigation information: either at a regular rhythm, or only when the next turn is close. In a preliminary online study, no significant difference of preference for one of these concepts could be stated, and participants rated visual maps applied in an unfamiliar environment as the system and situation most common for pedestrian navigation. A field study was conducted with seven conditions: each of the two distance concepts either as a visual, audio, or tactile version, and paper map navigation as control condition. Tactile and audio versions achieved the best performances regarding task completion time, and 47% of participants rated the guidance with tappings as least stressful. 60% did not recognise the difference between the two timing concepts which might be dues to the short way segments where never a longer period of no feedback occurred. Analysing the data according to the results of a pre-conducted spatial ability test, it appears that with a lower ability the preference for tapping increases, indicating at least spatially distributed vibrations are easy to map to a specific direction.

Special devices not using vibrations, but different kinds of haptic feedback were used for the following prototypes.
Amemyia et al. [1] and Amemiya and Sugiyama [2] created a kinaesthetic illusion of a pulling sensation. Their device, called force-sensation-based navigation system, applies a strong acceleration to the skin for a very brief time in one direction, followed by a weaker but longer acceleration in the reverse direction. Since people are not actually aware of the weaker sensation, only a unidirectional force is perceived and can be repeated for a continuous signal. A first study was conducted with 500 people (120 filled in a questionnaire afterwards) where people had to play the role of a waiter bringing glasses to tables. No one had problems perceiving the direction, and without training they achieved 83,3% correct deliveries. A second study with a further developed similar device was conducted with visually impaired people navigating in a maze, compared with

additional auditory feedback. No difference in walking pace could be stated, and the absence of audio information did not affect navigation performance. Moreover, participants found the system easy to understand and expected it to be useful in emergency navigation situations.
Sokoler et al. [93] introduced TactGuide, a device where little pegs under the thumb are raised to indicate four directions. In a user study with 7 participants, directional cues were easily identified and used, but because of the low accuracy (front, back, left, right), it cannot be used as sole source but only together with the environment to see if a left turn is more slight or sharp.

3.6.3 Using multiple vibrators

The next section summarises existing work, listed in Table 3.4, based on more complex devices using vibrators distributed around the body. By imagining a line between the body centre and the position where the vibration is perceived, directions are displayed.
Van Erp and van Veen investigated complex tactile displays for different application areas. In a cockpit simulator, they examined the effect of different G-loads on the perception of stimuli presented by vibrators attached left and right of the torso [107], and found that it is not substantially impaired during loads up to 6G. Furthermore, a tactile vest for astronauts to allow orientating in environments with zero gravity was developed [22], and the application in military environments was examined [21]. Van Veen et al. developed a belt with sewn in vibrators. A direction was indicated by vibrating at a specific position on the belt. Additionally, to communicate distance, different models were tested to the next waypoint. Either a 3 phase model was applied where information was given more often when close to the last or next waypoint, or a monotonic coding was used where the interval between vibrations was directly dependent on the distance to the next turn. Pedestrians were tested using the belt on a free field, where waypoints could not be identified visually [106]. After a short learning interval, participants were able to follow the ways, however, no differences of results could be detected regarding the codings of distances. In an experiment with flying a helicopter and driving a boat guided by vibrations, pilots and divers were able to perceive the displayed information easily and recognised the indicated directions, and a training effect was visible when participants got used to the new kind of feedback [24].
Tsukada and Yasumura [103] also developed a belt with eight vibrators (ActiveBelt) to intuitively present direction information and use it for location aware services like navigation or the highlighting of points of interest, as well as enhancement for music, by vibrations transmitting the rhythm. For the navigation task, distance is displayed as rhythm, shorter intervals between the vibrations indicate a shorter distance. A user study was conducted, where participants were presented the navigation information either while standing still or walking, where the focus lay on the possible values for durations of vibrations and pauses. Results show that direction was easy to perceive, especially at the front, back, left and right locations. All tested durations of vibrations could be sensed in the standing condition, however, performance was worse when walking. Short durations were hard or not perceivable when moving, and it took longer to understand the instructions, so it often occurred that a change was only recognised after some steps and the participants stopped for a moment before moving on.
Smets et al. [91] used a tactile vest, however, as only one horizontal line of vibrators was used, it was similar to the belts discussed before. The application area was the rescue of victims in an unknown environment, where orientation normally is maintained with floor plans. These can either be oriented north-up to maintain the overview easily with a high mental effort required to map plan and reality, or heading-up, which allows an overall faster completion of the navigation task, but at the expense of situational awareness. Tactile feedback indicating the overall direction was tested to help working with the north-up map, and thereby, decrease the time needed to find the way to a victim and back. A user study conducted in a virtual environment showed that when the north-up map was enhanced with tactile feedback, the mental effort was reduced to the same level as the heading-up map, and completion time was decreased, however, the heading-up map

Author	Interface	Experimental design
Van Veen et al. (2004) [106]	Belt with 8 vibrators, location for direction, rhythm/timing for distance	Comparison of different rhythms codings for distance
Tsukada and Yasumura (2004) [103]	Belt with 8 vibrators, location for direction, pulse interval for distance 	Testing concept and perception in standing and walking condition
Smets et al. (2008) [91]	Tactile vest, only horizontal line used, location for direction 	Investigation of effect of tactile feedback on speed and situation awareness
Heuten et al (2008) [37]	Belt with 6 vibrators, location and intensity for direction 	Open field test of concept
Pielot et al. (2008) [69]	Belt with 6 vibrators, location and intensity for direction	Comparison of discrete and interpolated vibrations regarding accuracy and easiness of perception
Pielot et al. (2009) [68]	Belt with 6 vibrators, location for direction, rhythm for distance	Test of giving overall direction to destination in combination with an overview paper map
Pielot and Boll (2010) [67]	Belt with 12 vibrators, location and intensity for direction, rhythm for different waypoints	Comparison with TomTom in city centre environment
Lindeman (2005) [56]	TactaBelt with 8 vibrators, direction indicates uncleared spaces	Application in first-person shooter game-like scenario
Spelmezan (2009) [94]	Vibrators attached to upper body around shoulders and thighs, combined vibration patterns to indicate directions	User study with snowboarding task, push and pull sensations while moving

Table 3.4 – Existing research using tactile feedback for a navigation task: using multiple vibrators

allowed an overall faster completion time. Spatial ability was shown to have a great influence on the performance and when using the tactile feedback, it got even more important.
Heuten et al. developed the Tactile Wayfinder, another belt including vibrational feedback to show the direction to the next waypoint. Only six vibrators were used, but by interpolating the intensities of adjacent vibrations, the range of possible directions was increased and an mean deviation of only 15° between presented and perceived direction could be shown [37]. In a first user study conducted on an open field with non-visible waypoints, the system showed first good results [37]. Further test were conducted to compare continuous and interpolated feedback of the belt [69]. Interpolated presentations showed more accurate results, in contrast, when directions were shown by vibrating discrete tactors, reaction times were shorter and it was said to be easier to perceive the direction. Another study was conducted in a crowded city centre to compare the Tactile Wayfinder,

now with 12 tactors and discrete feedback, with a commercial, visual navigation system [67]. To compensate the missing overview available with visual maps when only turn-by-turn instructions are given, the tactile feedback was expanded. Not only the direction to the next, but also to the one after that, called "look-ahead" waypoint, was presented. The two points were alternately indicated, and could be identified by a distinct rhythm. Significantly more near accidents were observed when using the visual system, indicating a higher workload when using the map as participants could not concentrate fully on their environment. Overall, only few navigation errors were made, however, the map-based navigation caused significantly less errors, on average 0.29 compared to 0.79 per route containing 6 decision points. A strong correlation was found between errors and acquired spatial knowledge, indicating that going wrong has not only an influence on completion time, but also on the overall orientation. Problems with the tactile feedback occurred when several ways close together were available, moreover, participants sometimes felt uncomfortable with the vibrations and like "bossed around" by the constant feedback. Their conclusion is that visual and tactile interfaces should be combined to benefit from both the visual overview and the reduced workload of the vibrational feedback. A first attempt was realised by Pielot et al. [68], who enhanced the usage of a paper map with the same belt to indicate the overall direction to the destination (similar to Robinson et al. [76], see Chapter 3.6.1), while the map was used to give an overview of the street layout, plan the route and look for shortcuts. The combination was compared to using only a map, and results show that with the belt, less consultations of the map were needed and less disorientation events were observed. The average walking speed achieved was slower with the belt, but shorter routes were taken, so the average travel time was shorter using the combined interface. The belt feedback was mainly used as a confirmation of the current direction, which is more complicated in the map only setting as it has to be done by identifying landmarks like crossings and matching them to the current position on the map. Another study was conducted with the belt, where information about positions of several other people [70] was given by vibrating. Different persons were indicated successively. Different variants of indicating distance were tested, where rhythm (less pulses = closer) and intensity (more intense = closer) led to better results and a better perceived level of simpleness than using duration (shorter = closer). A user study was conducted where the system was used for groups of people playing Counterstrike where a good situation awareness is critical for being able to win. Measures were achieved by subjective self-judgements, external observers and objective performance. When using the belt, compared to not using it, attentional resources were less demanded and better supplied, and a better subjective and objective understanding of the situation and improved teamplay due to better situational awareness could be observed. This indicates, that even with a high cognitive load while playing, tactile information can be processed effectively and the overall perception and processing improves. Additionally, participants commented that the vibrations did not distract them from the perception of other information and saw it as a useful enhancement.

Lindeman et al. [56] used a vibrotactile belt for a building-clearing task in a virtual environment, where on the one hand, targets had to be found, and on the other hand, spaces had to be cleared. A vibration in a specific direction indicated a not yet cleared space. Compared with performing the task without vibrotactile cues, subjects were exposed to uncleared areas a smaller percentage of time, and cleared more of the overall space when the tactile feedback was activated. Results show that with vibrations, participants took longer, but made more complete searches.

Spelmezan et al. [94] investigated the usage of motion to give instructions during physical activities. In a preliminary study, nine vibrators were attached to the upper body, and successively activated to create, for instance, motions around one or both shoulders to indicate a required turn. Participants preferred vibrations around both shoulders over one and patterns where each vibrator was activated once instead of three times. The main study extended those motions to the whole body, being received either as push or pull instruction. In relaxed and active conditions, recognition rates of more than 97% and 89% could be achieved.

4 Developing vibrational feedback

This chapter starts with a look at tactor technologies. After that, the process of developing vibrational patterns to use with the metaphor of the navigation radar is shown. Since the C2 tactor is controlled with audio signals, characteristics of sound and the resulting possible parameters for vibrations are presented before actual design consideration about how to assign the various parameters to navigation information are illustrated. Finally the developed patterns are described.

4.1 Choice of vibrator

4.1.1 Classification

Vibrotactile transducers can be grouped into two categories: inertial shakers and linear actuators [61]. Examples for inertial shaker are eccentric mass motors which are working like shown in Figure 4.1 a). The idea is to mount a weight eccentrically onto the motor's shaft. When the motor is moving this mass translates the operating forces onto the motor's shaft. Since this is fixed, forces are further translated onto the motor housing. This movement is then perceivable as a vibration. Figure 4.1 a) shows two configurations, where the eccentric mass is rotating either (1) orthogonal or (2) parallel to the skin.

In contrast, actuators mostly contain a linear contractor. Figure 4.1 b) shows the construction of a

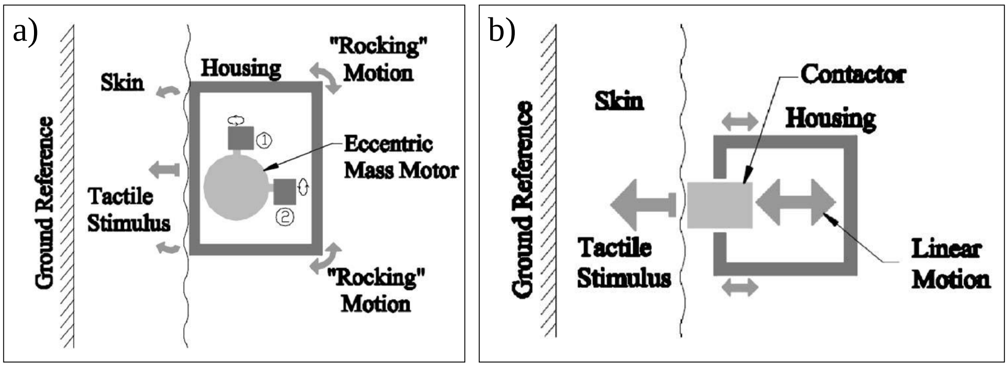


Figure 4.1 – Operational schematic for a) inertial shaker and b) linear actuator [61]

linear actuator. Both the contractor and the housing are in simultaneous contact with the skin. By independently moving the plunger-like contractor, the displacement is directly transmitted to the skin without the intermediate step over the housing. Additionally, a vibration can be provided at a specific point instead of a greater area. This makes it possible to distinguish between different locations close to each other.

4.1.2 Internal vibrator

Vibrators in mobile phones belong to the category of inertial shakers [83]. On Android phones such as the used Motorola Milestone it is easy to access through the API which provides a class called `Vibrator`. A `Vibrator` object can be retrieved using `getSystemService(Context.VIBRATOR_SERVICE)` from an active application. It allows to play single pulses or more complex pattern with its methods `vibrate(long[] pattern, int repeat)` and `vibrate(long milliseconds)`.

However, the drawback of the internal vibrator is that duration is the only parameter that can be changed. The fact that the motor needs some ramp-up time to reach full intensity can be used to influence the intensity to a certain degree. Short vibrations do not reach full intensity and are consequently weak, while for longer durations the motor reaches its full intensity and vibrations are perceived much stronger. Splitting a long vibration into a lot of short ones allows one to turn a strong vibration into a weak one; however, it does not work the other way round: a short vibration can never be as strong as a long one. Another point is that vibrations cannot overlap, so as soon as a second vibration is started from code the first one is stopped. That means you cannot increase or decrease a vibration's intensity because when a change is made the whole vibration starts again, at a low intensity level. Brown and Kaaresoja [12] compared the feedback of a mobile phone vibration motor and a linear actuator, presenting information encoded with rhythm and roughness. They report that it was no problem to present rhythm. However, roughness was simulated by an on-off pattern on the phone. It had only an identification rate of 55% compared to 80% on the C2 where roughness was realised with an amplitude-modulated sine signal. Additionally, it was not possible to get an intense and rough signal at one time due to the ramp-up time.

4.1.3 External C2 tactor

To have more options for changing vibration parameters, a linear actuator, the EAI C2 tactor [122], was chosen for the studies. This tactor has already been used in other studies like [96] and [8] and proved to be reliable and powerful. The vibrations are transmitted by the centre of the tactor, so the best perception is given when a fingertip is placed on this point. It can be controlled by audio signals, which can be provided by a mobile phone or a computer.

The Motorola Milestone's audio power out is controlled by the amplifier of the integrated TWL5030 audio/energy management device [66]. This provides the headphone jack with a load impedance of 32 Ω and a maximum output power of 61.25 mW [101, p. 68]. According to the C2's specification the recommended driver is an amplifier with typical 0.5 W. Therefore the outgoing signal is not strong enough and an additional amplifier had to be used. For this purpose a Fiio E5 was chosen. This amplifier is designed to improve the audio output of digital audio players, is very small (44.2mm x 38 mm x 12.6 mm) and provides an output power of 100mW for a standard audio out loaded with 32 Ω [29]. The resulting signal is enough to get wide ranges of sensations with the C2.

Hoggan et al. [41] also conducted a study where two different vibrators where used, the C2 tactor and the built in one of a Samsung i718 phone. It is highlighted that one advantage of the C2 is that it provides localised feedback only at the tip of the finger placed on the tactor, allowing them even to use spatial location as a parameter by placing two C2 on both sides of the device. They also state that the feedback given by the C2 was superior in terms of ramp up time and clearness of modulation.

4.2 Audio basics

To create vibrations on the C2 tactor it is connected to the audio port of a device. Similar to a speaker, where the membrane is oscillating to create sound, the C2 is controlled by sound. Sound waves can be affected by several factors. An overview is given in Figure 4.2. *Duration* describes the overall length of the audio signal (in *ms*), while *frequency* is the reciprocal of the period of one oscillation and measured in Hertz ($1/s$). *Waveform* characterises the shape of a wave, like sine, square or saw. The maximum change in magnitude during one oscillation is measured as *amplitude* and when the wave is not uniform like a simple sine signal, it can always be described as the *modulation* of different basic signals.

4.3 Vibration basics

Possible vibrational parameters can be classified by the design space presented by Sahami et al [83] that is depicted in Figure 4.3. How concrete parameters are assigned is summarised in Table 4.1.

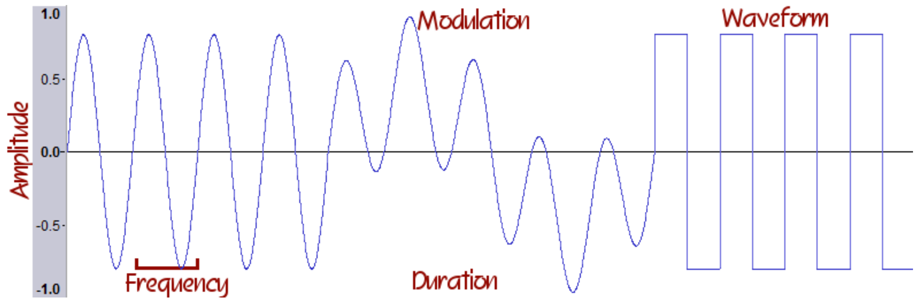


Figure 4.2 – Parameter overview for audio signals

For example, the axis *Time complexity* is regarded when with a single vibrator different pulses are successively presented, or when pulses of different durations are designed. These two aspects together result in a rhythm. With multiple vibrators attached to different locations on the body surface, the *Space complexity* is increased. Combinations of time and space result in parameters like motion and speed. Additionally, the *Pulse characteristic* of a single vibration can be changed by using the parameters intensity and roughness [117].

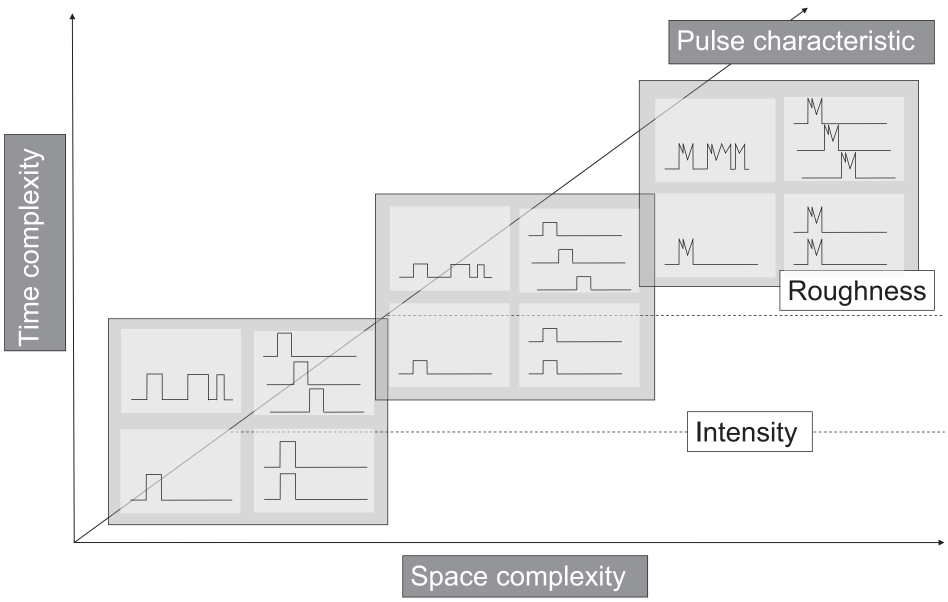


Figure 4.3 – Design space for vibration stimuli, adapted from [83]

Timing Timing in form of the radar metaphor introduces the main parameter used for all patterns. The main information for the navigation task, communicating the direction where to go next, is transmitted using this parameter. Users have to perceive the different intervals between the two vibrations. One presents the current vibration and is used to have a consistent indication of speed, while the timing of the other one communicates the direction of the next turn. To help users to get into this rotation, the metaphor of a radar is introduced. This rotates at a constant speed and a vibration occurs when it scans the current or desired direction.

Parameter	perceived as	time	space	single pulse
Timing	when to start (time)	x		
Duration	how long (ms)	x		
Rhythm	combination of vibrations and pauses (ms), number of pulses	x		
Location	where is a vibrator mounted		x	
Motion	when do different vibrators start	x	x	
Speed	combination of rhythm/motion	x	x	
Intensity	how strong how abrupt			x x
Roughness	how clean			x

Table 4.1 – Parameter overview for vibrational patterns

Duration Duration is a parameter that can easily be changed with every vibrator. In studies using multiple tactor devices such as belts [24] [56] or vests [91] often durations of one second are used to guarantee that a vibration at a certain location is clearly perceived. Other research has shown that shorter durations of 500ms while walking and 125ms while standing can be sufficient [103]. Pielot and Boll [67] even showed that using a heartbeat-like pattern consisting of two pulses with an overall duration of 400ms is perceivable on a belt while walking. However, when vibrators are attached directly to the skin, especially at very sensitive parts of the body such as a finger tip, durations can be much shorter. Qian [73] used 100ms as the minimum duration evaluating identifications rates of tactons, while 31.25ms was the shortest vibration included in a comparison of different vibration rhythms [100]. The evaluation of different vibrations to enhance touchscreen button clicks revealed that durations of 6-15 ms were already useful and rated as most pleasant compared to longer and shorter intervals [48]. Since the feedback produced by different vibrators varies and this study was conducted under silent conditions, these results cannot directly be applied to other situations. Contrary to this, Hoggan et al. used the C2 tactor for touchscreen feedback and conducted studies in underground trains [41] [42]. They showed that a 30ms vibration as touchscreen feedback for click events was unobtrusive but perceivable in this noisy and bumpy environment.
Having determined a minimum length, duration should be examined further as it can be useful to distinguish between different signals. For example, devices where vibrators are attached to wrists [4] or fingers [35] successfully used durations of 0.7 and 1.5 respectively 2.0 seconds to distinguish between information which refers to a ratio of about 1:2 respectively 1:3. Ryu et al. [82], who examined perceptual distances between different vibrations lasting 0.5, 1.0 and 2.0 seconds, found out that a ratio of 1:4 is preferred over 1:2.

To ensure that each of two successively presented vibrations can be perceived distinctively, a

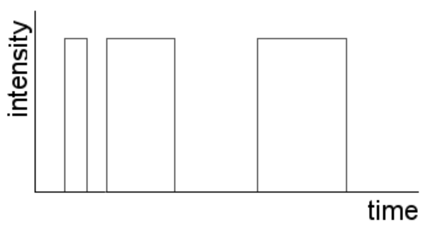


Figure 4.4 – Duration as vibrational parameter

sufficient pause has to be applied. Figure 4.4 shows pauses and vibrations of different durations. An interval of 15ms was used between two 10ms pulses in [15] while van Erp et al., who used vibrators built into car seats, chose 20ms for vibration bursts of 60ms [25]. Mortimer also suggest an minimum interval of 20ms to distinguish different stimuli [61]. Spelmezan who used different vibrators activated one after another to create a sensation of motion successfully used pauses of 50ms between vibrations of 100ms [94]. A different study investigated the minimum interval in more detail and found 27ms was sufficient when vibrations take 100ms, but when vibrations are extended also the pauses have to be longer, and 36ms respectively 83ms have to be applied for 200ms and 400ms vibrations [47]. These results show that pauses should be at least 20 ms long, however, the exact value depends on different factors such as duration of vibrations, and if one or more vibrators are used, and it has to be examined for each configuration what can be perceived.

Intensity Intensity of vibrations is the product of amplitude, frequency and waveform in the audio signal. Presenting an audio signal of higher intensity results in greater energy (*mA*) and, regarding the actual vibration, more displacement (μm) of the tactor's vibrating part. Amplitude can take a value of the range (0..1) to influence the sensed intensity. In the following, intensity is created by only changing the amplitude at a fixed frequency of 250Hz and with sine signals because with frequency and waveform no distinct signals could be created. The C2 tactor is most resonant at 250Hz, so signals with for instance 200Hz as well as 300Hz are less intense. Almost the same output can be reached by presenting a 250Hz signal with reduced amplitude of 0.3 and a 200Hz signal of maximum amplitude. Ternes and MacLean [100] showed that two amplitude levels could be clearly separated, however, for signals with varying frequencies of 200Hz and 300Hz no aggregate perceptual impact of frequency could be detected. This could be due to individual differences but also to the attenuation of the effect by short pulse durations of 427.5 ms maximum. Similarly, the waveform of an audio signal does not cause a considerably different resulting vibration, except that a square wave results in a more intense sensation than a sine or saw signal. It has been used as an additional parameter by Hoggan and Brewster in [41] and [40], however, only in combination with different other parameters so no direct comparisons have been conducted. A further possibility to influence the perceived intensity is to combine the internal vibrator of a device and an external one like done in CrossTrainer [40] or Shoogle [110].

Besides controlling the overall intensity of a signal, the way that signals are faded in and

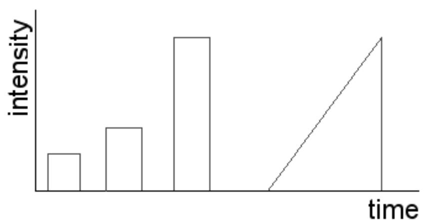


Figure 4.5 – Intensity as vibrational parameter

out also has an influence on the impression of vibrations. A linear fading makes the transition smooth, while an abrupt fading creates the impression of a sharp edge. Figure 4.5 shows three abrupt signals of different intensities and another one that is gradually faded in. Hoggan [41] and McAdam [59] explored different fadings for tactile touchscreen feedback where a faded smooth vibration was played for a mouser over event, while a sharp waveform indicated a click event. However, when signals are short, a linear fading mainly makes the signal weaker because the time of full intensity is shorter, and when the overall perceived signal strengths are adjusted to be similar, the difference is very subtle and only perceivable in direct comparison. The fading should therefore only be used for longer signals. Strachan et al. [96] created a continuous vibration only varying in intensity over time to communicate the progress of a curve, which can for instance present the noise level during a football game or the trend of a stock-market price. Another possibility is to use only one fading direction, that is a whole signal consisting of fading out or fading in to create a single decreasing respectively increasing sensation.

Roughness Roughness like in Figure 4.6 describes if a signal is perceived as clear or disturbed. Different roughness levels can be achieved by controlling the waveform. One way to do that is to change the basic waveform and use either square, sine or saw. However, changing this parameter for the C2 mainly affects the perceived intensity, and it is therefore no useful way to affect perceived roughness, as discussed in [10]. To affect the waveform more extremely and create a perceivable sensation of roughness, amplitude modulated signals can be used. Brown suggests to use sine signals of different frequencies and multiply them to create complex waveforms [10]. This technique has been applied in several studies such as [8] or [11] where at least 2 different levels proved to be distinguishable (80.56% of correct scores). A similar sensation can be achieved if signals are interrupted by short breaks, however, the creation of amplitude modulated signals is more straightforward and used below.

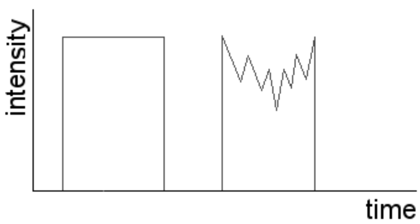


Figure 4.6 – Roughness as vibrational parameter

Rhythm Rhythms are constructed using multiple vibrations where the intervals of vibrations and pauses are varied. Rhythms have been successfully used to present directions [55] or message types [11], by varying the number of pulses and lengths for the different pulses. Similarly, Pielot and Boll [67] have used different rhythms to distinguish between directions on a tactile belt: a heartbeat-like vibration containing two pulses and a single pulse. Chan et al. [14] also designed their vibrations matching an audio equivalent. They imitated a heartbeat, and also the sound of plugging or unplugging USB devices: a longer weak followed by a short strong vibration or vice versa like shown in Figure 4.7. But the perception of rhythms is not always intuitive: Ferris and Sarter [28] used rhythms containing either one long up to four short vibration, however, not the impression of different pulse durations but counting the pulses was used to identify a rhythm. Qian [73] found that it is easier to identify rhythms that are static and not dynamically changing over time. According to Ternes and MacLean [100], the main impression of a rhythm results from the note lengths, so if it contains mainly long or short vibrations, and from the evenness of the rhythm. They also state that it gets easier to perceive a rhythm when it is repeated several times. An easy rhythm that consists of one or more pulses of equal duration can be changed in several ways to create distinct tactons. First, when a fixed number of pulses is used, the duration between those can be changed [60] [8] [25]. Another way, where the same overall duration is maintained, is to have more but shorter pulses. The main parameter is then still the number of pulses, not the changed duration [28].

Location Another way to create distinct sensations of vibration is to mount the vibrators at different locations on the body. For a navigation task, the mapping between vibration and di-

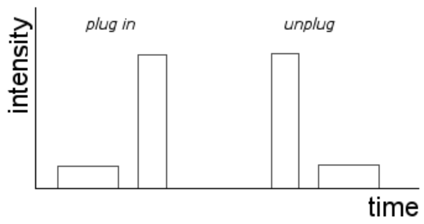


Figure 4.7 – Rhythm as vibrational parameter - metaphor of plugging USB devices

rection can directly and intuitively be performed [67]. Several studies have successfully used belts [37] [103] [24] [56] or vests [22] [91] where vibrators were sewn in, so the vibrations can be perceived on locations around the body. A more localised distribution was used for the GentleGuide [4] were tactors were attached to both wrists, or like in [11] where wrist, elbow and a position between of one arm were used. Using the punctual feedback of linear actuators (see 4.1.1) it is even possible to distinguish between different vibrators that are attached to a mobile phone [83] [38].

Motion Using different vibrators attached to several locations, a sensation of motion can be created. Activating them successively, can be used to present a movement, for instance rotational around the wrist [53] or the upper arm [47]. Van Erp used vibrators built into a car seat to create a movement from back to front [25]. Sahami et al. [83] used a mobile phone with six attached vibrators where directional motions could be perceived when using six vibrators, and Hoggan et al. [38] even created a circular movement with only three vibrators attached to a mobile phone.

Speed Changing the speed of a motion or rhythm can also be used to convey information, for example by shortening the pause intervals between vibrations [47]. Hoggan and Brewster [38] created a sensation of a circular movement, and successfully associated the getting faster with a more progressed download, while Lin et al. played rhythms slow or fast depending on the remaining distance to the next turn [55], which could be recognised easily. However, using speed is rejected because the main idea here is to establish a constant speed of rotation. Since this feeling is only based on a regular single vibration instead of vibrations around the whole circle, it would be too difficult to maintain it when variations of speed are applied.

4.4 Design considerations

In the following, it is discussed how the different parameters can be used to communicate the different navigation information direction and distance. Moreover, the process of selection of suitable combinations is described. Whenever possible, it was tried to figure out a metaphor for the association of characteristic and meaning, to minimise the cognitive load needed to decipher the patterns and to make them as intuitive as possible. However, some patterns are more abstract, and require therefore a higher degree of training and more effort to identify the meaning later, but offer possibly more expressive combinations [28].

Duration The durations of vibrations have been chosen according to the duration of one rotation. Different speeds were tested informally. Durations of about four seconds and longer seemed to be too long to establish a robust feeling for the whole rotation, while when using two seconds too many vibrations occurred to be properly perceived and processed. As a trade-off between receiving information often enough and at a comfortable rate, three seconds was chosen.

Duration was considered to be useful to distinguish between the two different directions. The minimum duration was set to 50ms. 200ms and therefore a ratio between short and long vibration of 1:4 was set as the maximum duration for the longer vibration. According to literature where this ratio has already proven to be discriminable this was chosen to ensure distinctness without being unpleasantly long. With a rotation duration of 3s, 200ms correspond to 24°. To allow to test the recognition of directions of 30° to the left or right and in the same time avoid that the vibrations overlap and include a sufficient interval in between, a shorter vibration of 150ms (≙ 18°) was applied for these two directions.
Duration is not considered as a parameter for the creation of more specific patterns for direction and distance. Pielot [70] successfully applied longer durations to longer distances, but since different durations are already used for distinguishing the directions of current and desired way, possible additional levels could only be created using even longer vibrations.

Intensity One possible application of using the change of intensity is to use a more intense signal when a close turn is presented. This has already been applied in spatial audio systems [95] [45] where people are guided by spatial sound where the source of sound represents the destination one is guided to. For tactile context, the association of intensity with distance has already been applied in [70] where closer objects are presented with higher intensity. Chang [15] showed that two (three) different intensity levels, high and low (and off), can be distinguished which will be associated with close and far (and no turn required).
Another possibility would be to present a more intense vibration when a greater respectively smaller angle is to be communicated. However, for direction this parameter will be excluded from considerations, at least in part (see next paragraph), because it doesn't seem to be useful that a more intense and thus more obtrusive signal is used for certain directions, while others are presented more unobtrusive, since all directions have the same importance.
In the case of using the fading aspect of intensity, it could be combined with adapting the duration of signals according to the angle, so a small angle is presented by a short in- or decreasing signal, while for a greater angle the vibration takes longer. The decreasing vibration can be used to display the desired direction on the left (which is equivalent to going too far right), with the most intense peak in the desired and flattening until reaching the current direction. In contrast to this, the feedback for indicating a desired direction that lies to the right would be indicated by an increasing vibration, starting at the current direction and reaching its peak when scanning over the desired one. Additionally a short pulse is played for the current direction to mark the end or beginning and maintain a regular signal. A metaphor for this pattern could be to compare the increase to the right to someone pushing in this direction, while the decrease from the left could be understood as a pulling sensation.

Roughness Roughness as a parameter can be used to indicate the distance. A rougher signal feels more obtrusive and as done in [12] it is likely to use it for urgency. Accordingly, a rough signal would indicate that the distance to the next turn is close whereas a smooth signal stands for a turn that is still far away and therefore not very urgent. Thinking of driving in a car, the roughness could also be associated with notifications applied to streets such as metal bulges between two lanes to make drivers aware of the change. In this case a rough feedback would also mean that something is happening soon and people should pay more attention now. Since only two levels (close and far) have to be transmitted the extreme values used in [11] are taken which are a pure 250Hz sine wave for smooth and the same wave modulated by 50Hz and 30Hz as rough.
Similar to this, roughness could also be a way to additionally transmit information about direction. A greater angle between current and desired direction, which means someone is going more wrong, would be associated with a rougher signal, as it feels more rough to drive at or over the edge of a street when losing the way. Likewise in [8] and [41], rough signals are chosen to present

error events while smooth vibrations represent events such as confirmations. However, thinking of walking on defined paths, it is not more or less critical to recognise a slight or sharp turn, so this coding is left out for the design of patterns.

Rhythm Rhythm can be used to present distance. As in parking aids in cars, or Geiger counters, a faster rhythm containing more and shorter pulses can be used to indicate that a obstacle, or in this case, a crossing, is coming closer. On the other hand, rhythms can be very distinct, and therefore be used to distinguish between different directions. To keep the identification of rhythms easy, very simple ones are used, containing either a single or a double pulse. In case of showing directions, the single short one is used for the regular indication of the user's heading, being maximum unobtrusive, and the double one for the direction to go.

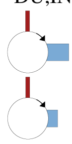
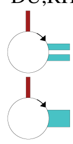
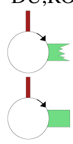
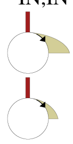
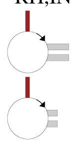
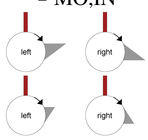
Motion Vibrational motion can be used to indicate a directional movement from left to right or vice versa. Considering that the C2 tactor is controlled with audio signals, stereo sound with differing intensities for left and right can be used to create this impression. It is applied additionally to the timing of vibrations, supporting the perception of the correct side.

Combinations The combination of roughness and rhythm is not used because with shorter pulses used to create a rhythm it is hard to recognise a certain roughness level. Rhythm is not used for both codings, to not confuse the meanings.
The codings for direction using fading, like the de- and increase to the left or right, or the directional movement from the left to the right (or vice versa) where the intensities of the single tactors are faded, are not combined with roughness, because using roughness takes away some of the signal's intensity. This results from the fact that the presented vibration it is no longer a pure 250Hz signal but a modulated one consisting of different frequencies. This reduced intensity range is not enough for creating the in-/decrease sensation. The combination with rhythm is also not considered in the following, because interrupting a faded signal takes away parts of the sensation of in-/decrease.

4.5 Chosen patterns

In the following, the remaining combinations of parameters to encode direction redundantly to timing and additionally display the distance are explained. The graphics always show a direction of 90° to the right. A close turn is indicated by the signal shown on top, a far turn by the graphic on the bottom. An overview is given in Table 4.2. The abbreviated descriptions contain two indices, with the first index relating to the coding of direction, the second one to distance.

Table 4.2 – Used combinations of vibrational parameters.

		Distance		
		Intensity	Rhythm	Roughness
Direction	Duration	$P_{DU,IN}$ 	$P_{DU,RH}$ 	$P_{DU,RO}$ 
	Intensity	$P_{IN,IN}$ 	-	-
	Rhythm	$P_{RH,IN}$ 	-	-
	Motion	$P_{MO,IN}$ 	-	-

$P_{DU,IN}$: Duration and Intensity In this pattern, two parameters are used: the two *directions* vary in duration, with a single, short vibration for the heading, a longer vibration for the desired direction. *Distance* is presented as intensity. An intense vibration corresponds to a close, a weak to a far turn. Figure 4.8 shows an overview.

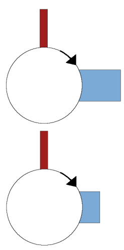


Figure 4.8 – $P_{DU,IN}$: Duration and Intensity (close - far)

$P_{DU,RH}$: Duration and Rhythm Duration and rhythm are used to present direction and distance (see Figure 4.9). *Direction* is distinguished by duration. To represent *distance*, a long single pulse is played for a turn far away, while for a close turn two vibrations are played. The overall duration of the two pulses is the same as the single long one.

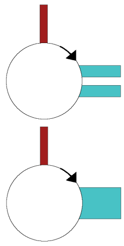


Figure 4.9 – $P_{DU,RH}$: Duration and Rhythm (close - far)

$P_{DU,RO}$: Duration and Roughness Again, duration is used to distinguish between the *directions*. *Distance* is now encoded with roughness. A more rough signal for a direction means one is close to the next turn, a smooth signal corresponds to a far turn. The overview is shown in Figure 4.10.

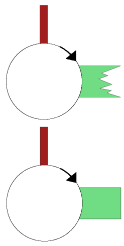


Figure 4.10 – $P_{DU,RO}$: Duration and Roughness (close - far)

$P_{IN,IN}$: Intensity and Intensity The current direction is presented as a short pulse. To present the desired direction, the intensity of a signal gradually changes. If the direction is on the left side, the vibration starts strong at this point and increases until the current direction, when on the right side, the vibration starts at the top and increases until the desired direction. The second variant is shown in Figure 4.11. Therefore, *direction* is shown by duration, timing in relation to the single short pulse and whether intensity is increasing or decreasing. Moreover, overall intensity of the signal is used to present *distance*; a weak signal represents a far, an intense a close turn.

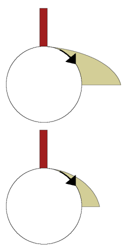


Figure 4.11 – $P_{IN,IN}$: Intensity and Intensity (close - far)

$P_{RH,IN}$: Rhythm and Intensity The pattern (see Figure 4.12) is similar to $P_{DU,IN}$: *direction* is encoded with duration and *distance* with intensity. However, to distinguish between directions, rhythm is used as an additional parameter. The vibration for the desired way consists of two short instead of one long pulse, where the two pulses overall take the same time as the one long pulse.

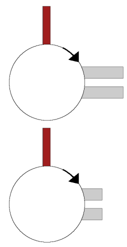


Figure 4.12 – $P_{RH,IN}$: Rhythm and Intensity (close - far)

$P_{MO,IN}$: Motion and Intensity In this pattern, two vibrators are attached to the phone. The two indicated *directions* can be distinguished by comparing the duration of vibrations: the current direction is a short pulse on both vibrators, while the desired direction is shown by a longer vibration. Additionally, the two vibrators create a directional movement from one side to the

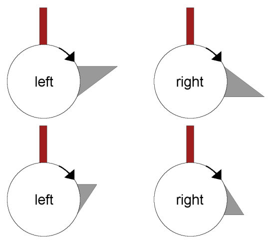


Figure 4.13 – $P_{MO,IN}$: Motion and Intensity (close - far)

other. Figure 4.13 shows how each of the vibrators is controlled and how motion is included in the longer vibration. If, for instance, the indicated direction is to the right, the intensity goes from left to right, by decreasing the left and simultaneously increasing the right vibrator's intensity. *Distance* is communicated with overall intensity: an intense vibration is presented for a close turn, a weak one for a far turn.

A design decision was made about the starting point of vibrations. When the vibration is presented during the imaginary radar scans the direction, like shown in Figure 4.14, the duration before and after the actual point are equal. However, informal tests showed that this leads to inaccurate results. It was described that the first impression of the signal, not a vibration as a whole, is perceived as the direction. Therefore, vibrations are started at the point the radar scans the direction so the perceived direction matches the actual one.

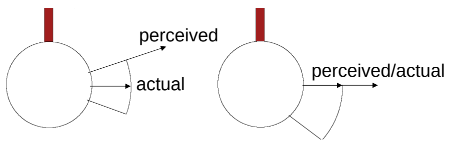


Figure 4.14 – Starting point of vibration before or at scanning point

5 Indoor study: The ideal vibration pattern

A comparative user study was conducted to advance the feedback concept. Participants were presented different vibrations and had to indicate where they would go on a circle. It allowed to gather information about how people can cope with the concept of imagining the rotation and to see how training effects affect the results. Moreover, the results can be used to identify differences in performance and ease of use of each vibrational pattern to refine the feedback. For screenshots and study material see Appendix A.

5.1 Prototype

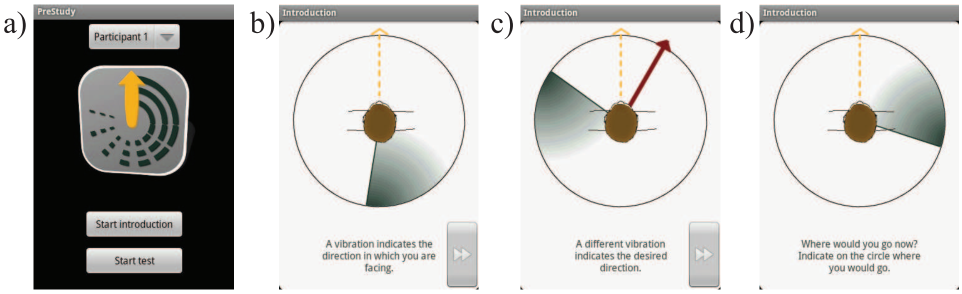


Figure 5.1 – Screenshots of the test application (1/2): a) Start screen b-d) Introduction of concept

Software The software for the prototype, written in Android, displays the testing interface, outputs audio to control the vibrations, receives the user input and logs time-stamped data. Each test run followed the same procedure. First, `StartActivity` (Figure 5.1 a) offers the possibility to choose a participant, and if the introduction or the next test should be started. `participant ID` and `finishedPattern`, determining the current study state, were stored as `SharedPreferences` to be globally available inside the application. The pattern and training order was hardcoded for every participant, whereas the distances and directions for trainings and tests were dynamically randomised for each participant with an adapted permutation algorithm [88]. A click on *Start introduction* leads to the next activity `GeneralTraining`, where participants are introduced to the concept of NaviRadar, and are presented the visual rotating radar for learning purposes (Figure 5.1 b-d). After that, a click on *Start test* starts the activity `PatternDescription` (Figure 5.2 a), where a description of the respective pattern is given. Another click leads to `PatternIntroduction1-3` (Figure 5.2 b), where, depending on the current pattern, a suitable path is shown with buttons at different stages, allowing to test the respective vibrations. Another click leads to the actual test activity `PatternTest` (Figure 5.2 c-d).

To realise the logging, the classes `CSVWriter` and `LogData` are implemented. For each general introduction and pattern test, a `CSVWriter` object is created, opening a new file with a unique filename. For each trial, an object of `logData` is created and successively, all attributes are set. A new object is created as soon as a new direction is presented, with the respective `participantID`, `patternID`, `direction` and `distance`. When a user input occurs, further fields like `angleInputStart` are set, and when the *next* button is clicked to finish this run, the `logData` object is passed to the `CSVWriter` object. Its function `writeData(LogData l)` then adds a new line to a comma separated CSV file using a `BufferedWriter`.

The radar rotation animation is implemented with a separate thread, constantly sleeping for the duration the radar needs to rotate one degree. Then, the main thread is notified using the `Handler` concept of Android, that is used to communicate between different threads. The instance of `PatternTest` holds a `Handler` that is passed to the `RotationThread` object at creation time. A `Bundle` is created to pass values, like in this case the current heading.

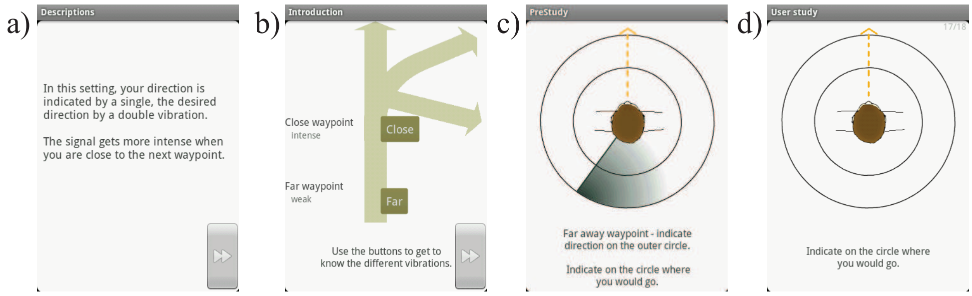


Figure 5.2 – Screenshots of the test application (2/2): a) Pattern description b) Pattern introduction c) Pattern training d) Pattern test

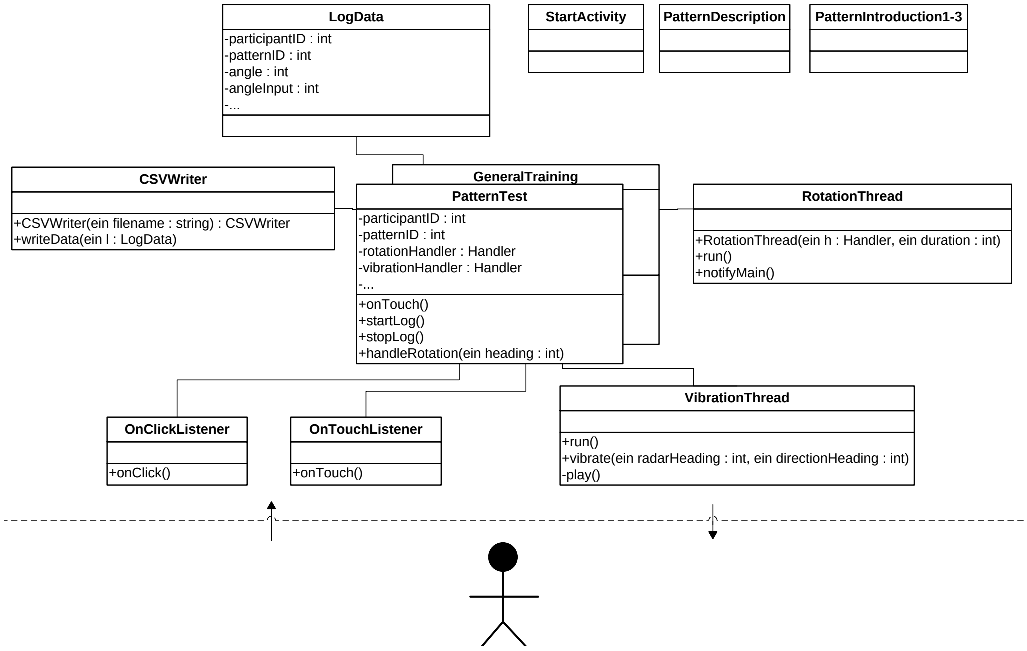


Figure 5.3 – Indoor study: Class diagram for prototype application

```
private void notifyMain(int current_heading){
    Message msg = mHandler.obtainMessage();
    Bundle b = new Bundle();
    b.putInt("heading", currentHeading);
    msg.setData(b);
    mHandler.sendMessage(msg);
}
```

On the other side, the `Handler` object implements a function to unpack and process the message.

```
public void handleMessage(Message msg) {
    int heading = msg.getData().getInt("heading");
    handleRotation(heading);
}
```

The radar graphic, a half transparent png image, is implemented as a rotatable view, a subclass of `ViewGroup`, and is then set to the current orientation. Additionally, it is checked if the current heading and one of the two directions for user heading and desired direction match. If they match, a sound file is played to create the respective vibration. All sounds have been preloaded as `MediaPlayer` objects to avoid lags caused by allocating memory.

```
...
MediaPlayer mp_50MS_STRONG = MediaPlayer.create(context, _50MS_STRONG);
mp_50MS_STRONG.setOnCompletionListener(new MyOnCompletionListener());
...
private class MyOnCompletionListener implements OnCompletionListener{
    @Override
    public void onCompletion(MediaPlayer mp) {
        while(mp.isPlaying()){}
        mp.seekTo(0);
    }
}
public void vibrate(int id){
    MediaPlayer mp;
    switch(id){
        case _50MS_STRONG: mp = mp_50MS_STRONG;
        ...
    }
    mp.start();
}
```

User input is processed by an `OnTouchListener` listening to touch inputs on the whole screen. It receives a `MotionEvent e` only accepting inputs on the circle with `if (e.getX()>250 && e.getY()>300 || e.getX()<=250 && e.getY()>350) return;` and uses Pythagorean theorem to compute the distance between the centre of the circle and the input coordinates to set either a short or long input arrow.

Hardware Figure 5.4 shows the prototypes with either one or two C2 tactors attached on the backside of a Motorola Milestone. The tactors were equipped with a headphone plug by soldering its wires to a 3.5mm adapter. In the case of two C2s, each one is connected to either the left or right audio channel wire. First, it was planned to run the application on the phones, but the small screen makes it difficult to input directions accurately. Therefore, it was run on an Android emulator on a laptop, and participants could use a mouse for input. The emulator ran the operating system version 2.2, as this offered the fastest performance, and contained an emulated sd card to store the log data. The log data was accessed with the Android Developer Bridge (ADB) command line tool, such as `adb pull /sdcard/201006101435231.csv data\201006101435231.csv`. The output power of the laptop's headphone jack was tested to provide the same intensities as did the mobile phone one's, so the changed platform did not require to adopt the audio signals and volume. As the emulator software did not run very resource efficient, it was made sure that no other time consuming processes were running and the system was rebooted after each participant to avoid lagging of the radar animation.

5.2 Study settings

The study was conducted in a quiet lab setting. Participants were asked to wear headphones (Philips SBC HP400) to block audio cues from the system that might affect participants' performances. This is common practice in experiments testing tactile feedback like [12], [39] or [38]. Additionally, a mix of white noise like for instance in [14], [15], [19] and [47] and typical street noise[1] like in [48] was played. This allowed to create a more realistic, distracting environment. It

[1] by Nathanial Freitas, provided on `www.freesound.org` under a Creative Commons Sampling Plus 1.0 License

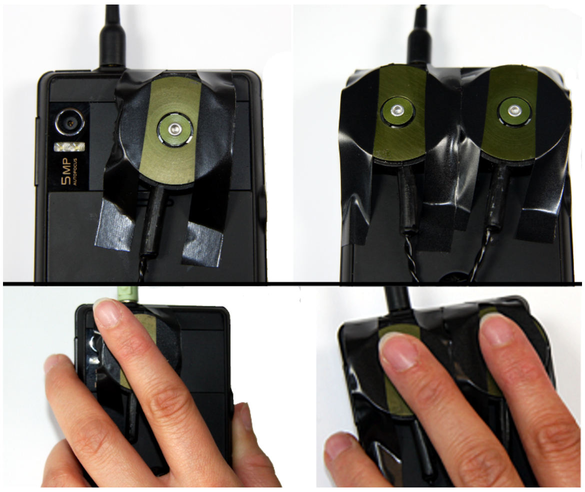


Figure 5.4 – Indoor study: Prototypes with one respectively two C2 tactors attached

was looped to be played seamlessly for a longer time by cross fading end and start. White noise was added because the street noise had some quieter sections where otherwise the sound of the vibrators could have been heard. This was done using Audacity 1.3.12. The headphones were attached to one of the phones as the headphone jack of the laptop was already used for the audio output controlling the vibrational feedback. During the study participants sat in front of the laptop (Sony Vaio VGN-NR11Z) like in Figure 5.5, felt vibrations of the phone in their left hand and used their right hand to control the mouse (Logitech LX7) and input what their sensed.

Figure 5.5 – Indoor study: Study setup

5.3 Participants

Twelve participants, six female and six male, took part in the study. They were recruited through posters distributed around campus of Lancaster University. Participants from a wide range of disciplines were selected. The age ranged from 19 to 32 with a mean age of 21.33 years ($SD = 3.72$). One of the participants was left-handed. However, since they used their right hand when controlling the mouse, all participants were effectively right handed and it follows that for the tests all participants held the mobile in their left hand.
On average, they rated themselves as highly experienced with computers ($M = 3.92$, $SD = 0.66$ on a scale from 1 = None to 5 = Expert) and mobile phones ($M = 3.67$, $SD = 0.77$). All of them had used car navigation systems before, whereas only four had experience with electronic pedestrian navigation systems. All twelve participants had experience with some kind of vibrational

feedback like the vibration alarm when a mobile phone is in silent mode (100%), game controllers with vibration feedback (92%) or vibrations as touchscreen enhancement (58%).

5.4 Experimental design

A within-subjects design with repeated measures was used, since individual performances were expected to vary because of different experiences and sensitivity concerning tactile feedback [53]. This was a way to equally distribute this variation across all conditions because every participant performs every task. This design also ensured that the maximum amount of measures could be obtained.

5.4.1 Independent variables

Three different independent variables were used in this user study. Six patterns were tested to present nine different angles in two distances. This results in overall 1296 data units for interpretation.

12 participants ×
6 patterns ×
9 direction angles ×
2 distances = 1296 data units

In the following, their levels are specified. Moreover, it is described how the different independent variables were distributed over participants during training and test phases to avoid that systematic orders affect the results.

Vibration pattern The six levels of the independent variable *Vibration pattern* apply to the different parameter settings described in Chapter 4.5. Vibration patterns were counterbalanced using Latin squares constructed with the procedure of [5, p. 525-528]. This ensured that the order in which the various conditions occurred was equally distributed: every condition appears as often as the others at each position and also every combination of subsequent pattern only appears once to completely eliminate order effects. The size of the Latin square always depends on the number of test conditions. Since for this user study it was used to counterbalance the different vibration patterns, it can be described by the 6*x*6 matrix shown in Figure 5.6:

$$\begin{pmatrix} 1 & 2 & 3 & 4 & 5 & 6 \\ 2 & 4 & 1 & 6 & 3 & 5 \\ 4 & 6 & 2 & 5 & 1 & 3 \\ 6 & 5 & 4 & 3 & 2 & 1 \\ 5 & 3 & 6 & 1 & 4 & 2 \\ 3 & 1 & 5 & 2 & 6 & 4 \end{pmatrix}$$

Figure 5.6 – 6*x*6 Latin square design

Distance Different levels for *Distance* were included in the user study. Regarding the characteristics of navigation systems, three levels can be distinguished:

1) No turn within reach

2) Turn is coming up but still far

3) Turn is close

The situation where no turn is within reach is later represented by a simple heartbeat which serves as a confirmation that the system is still alive but does not give a new direction. Hence this level was not tested in this study. The remaining two distances 2) and 3), representing that a turn is now within reach or already close to the current position, were used for the study.

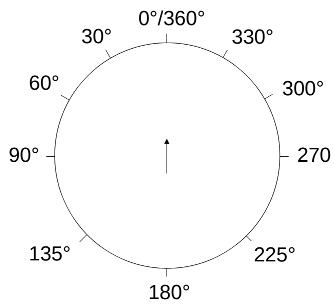


Figure 5.7 – Indoor study: Different presented directions

Direction angles The nine different directions shown in Figure 5.7 were tested to be recognised by the participants. A broad range of angles around the whole circle was chosen to test every direction that could be indicated by a navigation system. The angles were taken in 30° steps for the smaller and 45° steps for the larger angles. This accounts for situations when someone is to be guided to a specific point, and slight adjustments have to be made when coming close.

Training phase The distance signals for each level were introduced during the training phase. Participants were trained a new pattern first with the vibrations for a close turn and then for a far turn, or vice versa. The order of *distances* in the trainings runs was alternated after each pattern. Using the above described orders for vibration patterns twice and changing the starting order after six participants, participants 1-6 were trained close-far, far-close... and participants 7-12 in the order far-close, close-far... This ensured that every pattern was trained at each position with both orders of training distances. The resulting study design is summarised in Figure 5.1. Additionally

	1st test		2nd test		3rd test		4th test		5th test		6th test	
Participant 1	6	FC	1	CF	2	FC	3	CF	4	FC	5	CF
Participant 2	1	FC	3	CF	6	FC	5	CF	2	FC	4	CF
Participant 3	3	FC	5	CF	1	FC	4	CF	6	FC	2	CF
Participant 4	5	FC	4	CF	3	FC	2	CF	1	FC	6	CF
Participant 5	4	FC	2	CF	5	FC	6	CF	3	FC	1	CF
Participant 6	2	FC	6	CF	4	FC	1	CF	5	FC	3	CF
Participant 7	6	CF	1	FC	2	CF	3	FC	4	CF	5	FC
Participant 8	1	CF	3	FC	6	CF	5	FC	2	CF	4	FC
Participant 9	3	CF	5	FC	1	CF	4	FC	6	CF	2	FC
Participant 10	5	CF	4	FC	3	CF	2	FC	1	CF	6	FC
Participant 11	4	CF	2	FC	5	CF	6	FC	3	CF	1	FC
Participant 12	2	CF	6	FC	4	CF	1	FC	5	CF	3	FC

Table 5.1 – Counterbalanced study design[2]

[2] 1 = $P_{MO,IN}$, 2 = $P_{DU,IN}$, 3 = $P_{DU,RH}$, 4 = $P_{DU,RO}$, 5 = $P_{IN,IN}$, 6 = $P_{RH,IN}$, CF = close-far, FC = far-close

to this order of pattern and distances, directions were randomly taken from the full set of nine available angles.

Test phase For the test runs, the order for the 18 combinations of two different distances and nine different direction angles were randomised for each participant and pattern.

5.4.2 Dependent measures

Quantitative data Different quantitative performance measures were taken during the user study. This data was collected automatically by the prototype application and was saved to files in CSV format to easily import it to Excel and SPSS. Training runs were logged as well to be able to check which directions had been trained there. Each data set refers to one trial and consists of data about the current setting (pattern, direction, distance, current position) and several performance values. Information describing the participant's input was *angle input*, *angle deviation*, *distance input* and *distance accuracy*. These values were logged for the inputs' start and end time (as corrections were possible) together with the numbers of *times the vibrations for current and desired direction* had been played. Five different timestamps were taken as shown in Figure 5.8. First the time when the *Next* button is pressed, which corresponds to when the *new settings is set* internally, was logged. The next timestamps are the *first vibration of the current* as well as of the *desired direction*, the order of these depends on the time the *Next* button is pressed because the rotation does not stop after each trial but always goes on. Another two timestamps are taken for the *first and last input event*, so it can be checked how long the participant took to make corrections after his first input. If the input is corrected more than one time, only the last timestamp is logged. From

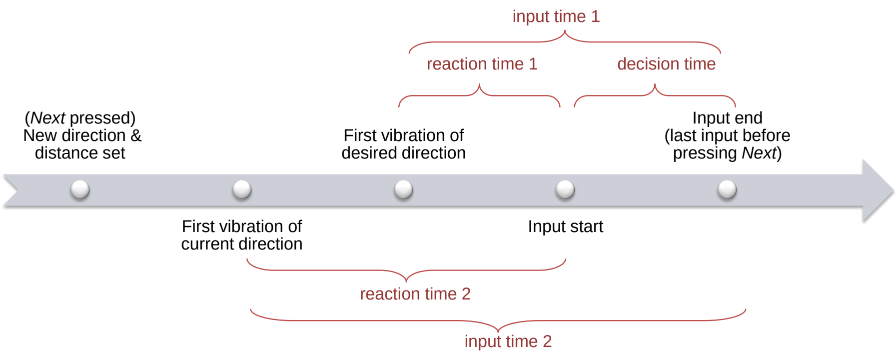


Figure 5.8 – Indoor study: Timeline for logging timestamps

these timestamps different time periods (in *ms*) are directly computed and logged. *Reaction times* describe the periods between a signals first appearance and the first input event, the *decision time* specifies the period between start and end of the participant's input. *Input times* include reaction and decision time.

Qualitative data After each test phase, participants were asked to fill in the post-questionnaire to collect subjective ratings of the latest completed pattern. They were presented with four different statements regarding *clearness* and *intuition* of the representations of direction and distance. For each statement they had to decide for one element of a five-point Likert scale ranging from *strongly disagree* to *strongly agree*. The perceived *mental effort* had to be rated with possible answers ranging from *very high* to *very low*. Then participants were asked to rate the just completed pattern on a seven-point range from *very bad* to *very good*, since it would have been very hard for participants to remember the details for each pattern in the end in order to achieve a comparison. From these values, an overall rating could be created afterwards. In the end, participants were asked if they could imagine any metaphors or if they had anything in mind to easily remember the pattern, or if they had any additional comments.

5.5 Procedure

First participants had to sign a consent form, this introduced them to the subject of the study, namely to test vibrational feedback for pedestrian navigation. Moreover, it gave them some information about how the study was organised. They were also ensured that all their data is kept in confidence, that the execution could always be stopped and confirmed that taking part is voluntary. Before the study started they were also asked to fill in a short demographic questionnaire.
Following this, participants were shown the study phones with the attached vibrator(s) and were told to always put their finger on the middle of them. In a test run before the actual user study the test participant mentioned that his hand became uncomfortable from holding the phone in this unnatural position with his finger tip held onto the middle of the C2 tactor(s) attached to the middle top part of the phones. Therefore, all participants were asked if holding the phone like this is comfortable, otherwise, the position of the vibrator could easily be moved to fit their needs. None of the participants made use of this.
Afterwards, they were introduced to the general concept, the interplay of imaginary rotation and vibrations. For learning purposes, at this point they could see a radar rotating on the screen which was not visible in the tests later. Having completed this part participants were encouraged to ask if they had any questions now or during the study. Then the introduction to the first pattern started: a written as well as an oral explanation was given, then participants could test the different vibrations as often as they wanted to get to know the differences between signals. For the following part, participants were asked to put on the headphones and the trainings phase for this pattern started where they had to recognise four different signals. They were told which of them were representing a close or a far distance, respectively, to ensure they learned how to input each distance. The order was counterbalanced among participants. In the training runs, participants could again see the radar animation as a the graphical aid for the rotation and the correct direction after inputting their guess. In the following 18 test runs they just got vibrational feedback and did not see the solution afterwards but were presented with the next direction right away after inputting and pressing next. Directly after a test run was completed, participants were asked to answer seven questions concerning subjective rating of the just finished pattern. Therefore the researcher read the questions out load and wrote down the answers. This was done to avoid a rushing through the questionnaire and to get more detailed results and comments. The same procedure was repeated for each of the remaining five patterns.
During the study notes were taken of comments and exceptional behaviour. After the study, that took between 45 and 50 minutes, participants received a compensation of £8 and were asked to sign a participant payment form.

5.6 Hypotheses

H1) The perceived direction is influenced by the vibrational presentation.
(Directions can be recognised using the imagined rotation)

The vibration pattern has an influence on the

H2) ... deviation of input from the communicated direction

H3) ... accuracy of distance identification

H4) ... input time

H5) The identification of direction is independent of the displayed distance.

5.7 Results

This section will show the results of the indoor user study. Unless otherwise stated, all effects will be reported at a .05 level of significance. The three main quantitative performance measures taken are the deviation between presented and perceived direction, the accuracy of distance recognition and the input time. Subjective ratings of representations and mental effort make up the qualitative part. Data from the introduction and training is not included in the analysis.

5.7.1 Recognition of direction

Absolute input The most important aspect of a navigation system is that it shows the user the correct direction. The scatterplot in Figure 5.9 shows the input values for each of the presented direction angles. In the bottom left and top right corner it can be seen that, especially for small angles, the sides were confused, for example, when presented 30°, some input angles are smaller than 0°. Mauchly's test violated the assumption of sphericity for the main effect of angle

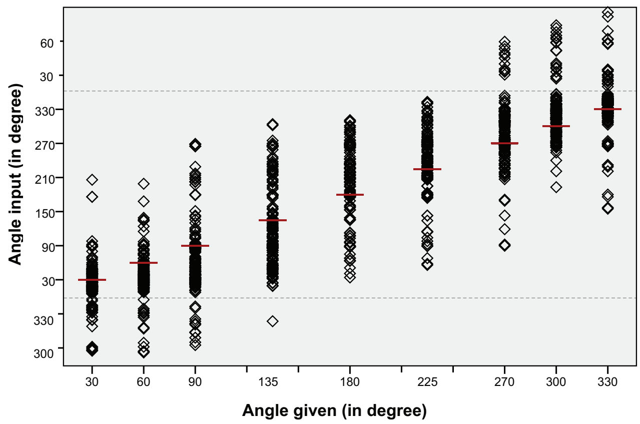


Figure 5.9 – Input distribution for each angle, red lines show the correct angle

($\chi^2(35) = 55.18$), so the degrees of freedom were corrected using a Greenhouse-Geisser correction ($\varepsilon = 0.32$). Results show a significant effect of angle ($F_{2.56,28.20} = 331.13$, $p < 0.001$) showing that the inputted direction is dependent on what is presented. This supports the hypothesis that the basic concept of recognising directions by imagining a rotation works. However, Bonferroni corrected post-hoc tests revealed that not all angles were perfectly distinct. The pairwise comparison showed that the combinations 30°/60°, 60°/90° and 300°/330° did not lead to significant different input values. This indicates that smaller angles are hard to distinguish which would cause problems for example when a crossing offers multiple ways to go slight left. However, tested directions were not equally distributed over 360° but more narrow (30° instead of 45° intervals) in the front area, making it harder for those directions to be distinct.

A different view on the data is given in Figure 5.10, where for each presented direction (outside of the circle), the mean input values are shown (inside of the circle). On average, the values are too close to 0°/360° on both sides, for instance, the average input for 90° was 68°, indicating that participants tended to underestimate the shorter intervals. But overall, there were no deviations of more than 30°. Pearson correlation coefficients ($N = 216$, $p < 0.001$) shown in Table 5.2 were computed to assess the relationship between the direction that was presented (angle given) and recognised (angle input). For all patterns there was a strong positive correlation confirming [H1] that says that it is possible to communicate directions with the used techniques. However, the actual input values in Figure 5.9 and the standard deviations in Table 5.3 show that there was a wide spread of input values.

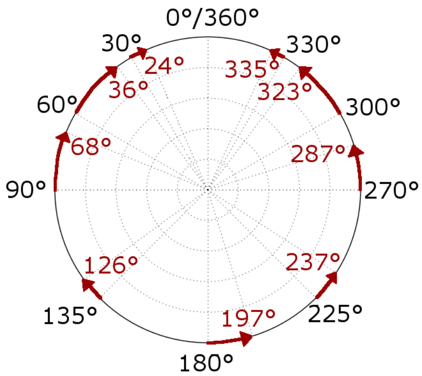


Figure 5.10 – Mean input values for each angle given

	$P_{DU,IN}$	$P_{DU,RH}$	$P_{DU,RO}$	$P_{IN,IN}$	$P_{RH,IN}$	$P_{MO,IN}$	Overall
r	0.87	0.90	0.92	0.86	0.92	0.87	0.89

Table 5.2 – Correlation coefficients for the relationship between presented and recognised direction

Deviation from communicated angle The deviation from the communicated angle describes the amount the input differs from the actual given direction. This error is critical for a navigation task especially when there is more than one turn for left or right. On average, participants were

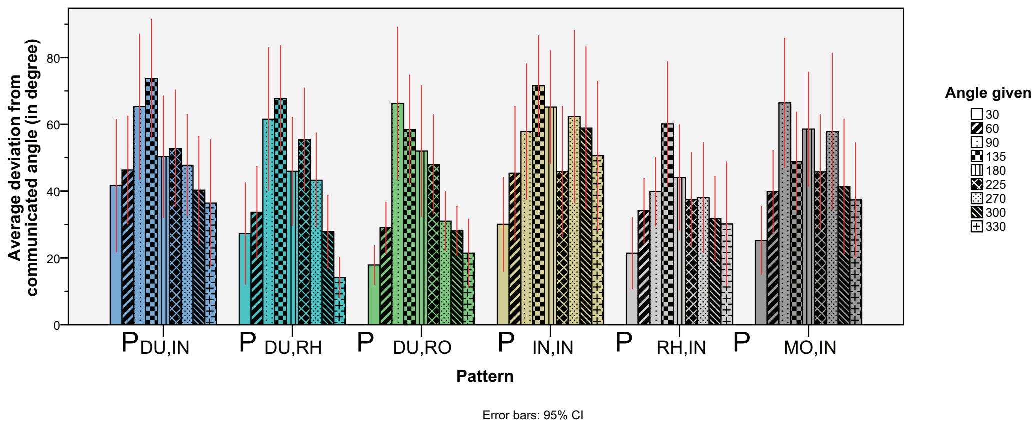


Figure 5.11 – Mean deviation from communicated angle per pattern, split by angles

able to specify the direction with a mean deviation of 44.99° ($SE = 3.98$). Figure 5.11 shows the mean deviations in each pattern setting. Mauchly's test violated the assumption of sphericity for the main effect of pattern ($\chi^2(14) = 26.92$), therefore degrees of freedom were corrected using the Greenhouse-Geisser correction ($\varepsilon = 0.47$). The main effects of pattern ($F_{2.35,25.89} = 4.92$), distance ($F_{1,11} = 15.31$) and angle ($F_{8,88} = 18.05$) were significant.
Bonferroni post-hoc tests revealed a significant difference between patterns $P_{IN,IN}$ and $P_{RH,IN}$, showing that when $P_{RH,IN}$ is used, input values are on average closer to the communicated angle. This confirms [H2], saying that the pattern can have an impact on the performance. The worst results with a mean deviation of 54.19° was achieved for $P_{IN,IN}$. Comments after the tests highlight that small angles were harder to perceive, because for small angles, and therefore short signals for the desired direction, the feedback mainly consisted of two pulses, the beginning respectively end

	30°	60°	90°	125°	180°	225°	270°	300°	330°
Mean input	23.53°	36.24°	67.94°	125.95°	197.10°	237.22°	287.11°	322.92°	335.23°
SD	41.59°	44.40°	72.66°	74.17°	64.61°	60.30°	61.81°	49.83°	50.97°

Table 5.3 – Mean input value and standard deviation per angle given

	$P_{DU,IN}$	$P_{DU,RH}$	$P_{DU,RO}$	$P_{IN,IN}$	$P_{RH,IN}$	$P_{MO,IN}$	Overall
Mean deviation from communicated angle	50.51°	41.88°	39.13°	54.19°	37.45°	46.81°	44.99°
Clear & understandable	4.00	3.91	3.55	2.55	4.09	3.36	3.58
Intuitive	4.00	3.82	3.64	3.18	3.91	3.45	3.67
Correct side	74.1%	81.0%	83.3%	69.9%	85.6%	77.3%	65.7%

Table 5.4 – Performance measures for recognition of distance. Subjective ratings were given on a scale from 1 = Strongly disagree to 5 = Strongly agree

of the decrease or increase, and the pulse for the current direction. As the signal duration was not sufficient for everyone to perceive the change of intensity, sometimes it was not clear if the second vibration belonged to the direction signal (and the peak was the end of the increasing signal or beginning of the decreasing one) or indicated the current direction. Additionally, participants rated this pattern as the worst pattern regarding clearness and intuition.

Regarding distance, the mean deviation for close turns ($M = 42.34, SE = 3.81$) was significantly smaller than for far turns ($M = 47.64, SE = 4.26$). This indicates that direction was easier to understand when a close turn as presented and [H5] (same performance for all distances) has to be rejected. Looking at the results for $P_{MO,IN}$, contrary to all other patterns, the direction was recognised less precise when a direction was close, ($M = 50.96, SD = 6.14$) than when far ($M = 42.65, SD = 3.50$). Since the "moving" sensation that was designed to help participants was more obvious for close turns because the intensity was higher and easier to perceive it might have irritated. Moreover, one participant commented that the movement from right to left was easier to perceive. The means for both sides are the same, however, the standard deviation for right-left ($M = 45.07, SD = 37.17$) is smaller than for right-left ($M = 45.59, SD = 46.36$). Other participants mentioned that even if the motion vibration got more obvious during the tests it did not help to recognise the direction.

Looking at the influence of a specific angle, a result worth mentioning is that the greatest, and therefore worst, deviation was achieved for an angle of 135° (sharp turn to the left) with a mean deviation of 63.40 ($SD = 4.26$). This did not differ significantly from the neighbour direction 90° and 180°, but was worse than for all others ($ps < 0.05$). The reason could be that this angle lies at a point of the rotation where the reference point *current direction* is far away, and the fact that it lies on the left side suggests that it is easier to perceive the interval after than before this point.

Influence of coding Different codings have been used to distinguish between the two directions that are presented in every rotation. The current direction is always indicated by a short pulse, so the differences between the codings lie in how the desired direction is presented. Figure 5.12 shows the performances of the different alternatives: The stereo signal is used to create the left-right/right-left motion in $P_{MO,IN}$. When using duration as the parameter, a long intense pulse is used for the desired direction in $P_{DU,IN}$, $P_{DU,RH}$ and $P_{DU,RO}$, where it either represents a close or a far turn. The increasing/decreasing sensation is used for direction in $P_{IN,IN}$. Finally, rhythm is used in $P_{RH,IN}$ and $P_{DU,RH}$, where a double pulse represents the desired direction.

The best performance regarding the deviation between presented and perceived direction of 36.68°

was observed when rhythm was used ($SE = 2.32$). Using duration or change of intensity show about the same results, while when the direction is encoded with motion from one side to the other, the worst deviation of only 50.96° ($SE = 4.28$) was achieved.

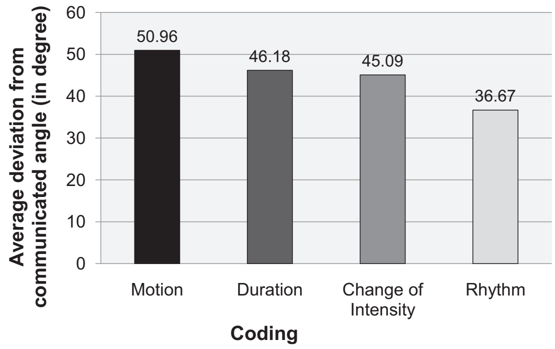


Figure 5.12 – Mean deviation from communicated angle per coding[3]

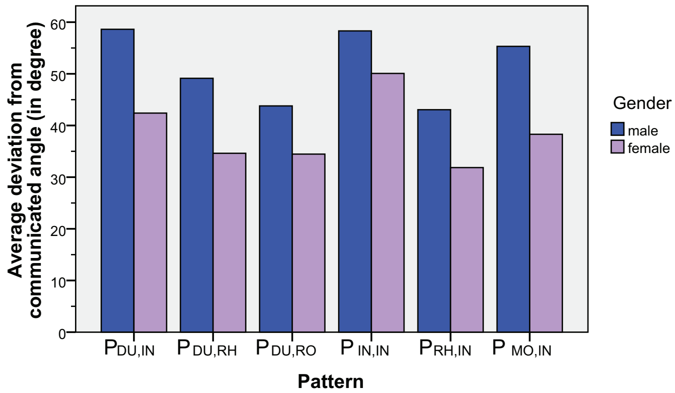


Figure 5.13 – Mean deviation from communicated angle, split by gender

Gender specifics Figure 5.13 gives another view on the data, where results are compared split by gender. On average, women achieved a lower mean deviation value ($M = 38.62$, $SE = 5.17$) than men ($M = 51.37$, $SE = 5.17$), indicating that they recognised the presented direction more accurately. This was the case no matter which pattern was tested. A possible reason could be that the participating men tried less hard to achieve good results than the women. The result at least shows that women are not disadvantaged by the system, which is in contrast to the results of [84] or [67] where women showed a worse sense of direction and a worse performance in tasks that require spatial visualisation skills.

Clearness and intuition Figure 5.14 and Table 5.4 show the results of the subjective ratings concerning if participants found a pattern clear and understandable. When a system is rated as easy, people can have more confidence in it and are more willing to use it. Friedman's ANOVA was used to analyse the data in terms of significant differences. The ratings for clearness were significantly affected by the pattern they had just used ($\chi^2(5) = 18.57, p < 0.01$). To follow up this finding, post-hoc tests were conducted. It appeared that using $P_{IN,IN}$ affected the rating if a

[3]For this comparison, only intense and not-rough vibrations are regarded since the results concentrate on the recognition rate of direction

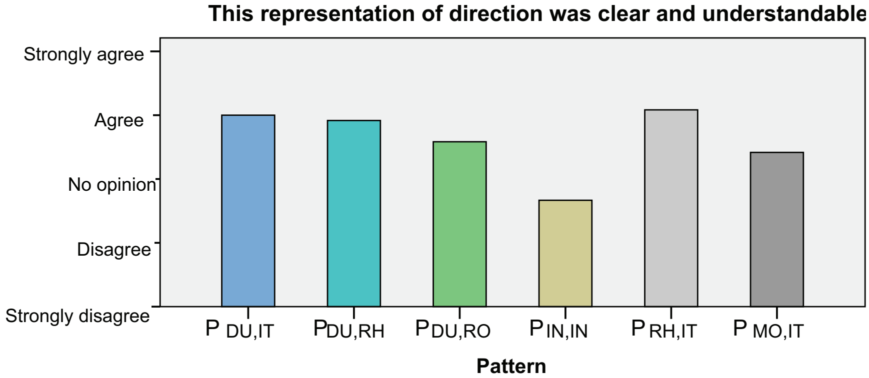


Figure 5.14 – Average rating for clearness of direction

pattern was clear and understandable negatively compared to $P_{DU,IN}$, $P_{DU,RH}$ and $P_{RH,IN}$. This supports the trend seen in the results of the mean deviation: $P_{IN,IN}$ achieved the worst values regarding deviation as well as the worst ratings regarding clearness of direction representation. Moreover, the lowest deviation values and best rating for clearness was found for $P_{RH,IN}$. Participants were also asked how they would rate the intuition of direction, however, the results show no significant differences for the different patterns ($p > 0.05$).

Correct side Another way to look at the results is to check whether participants could tell at least if the desired direction was on the left or right. Figure 5.15 shows the numbers of directions correctly recognised per pattern, for mean percentages see Table 5.4. Mauchly's test violated

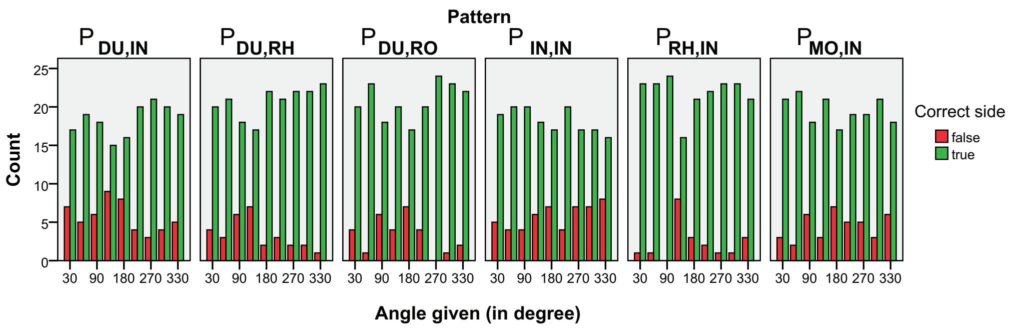


Figure 5.15 – Input on correct side per pattern, split by angles

the assumption of sphericity for the main effect pattern ($\chi^2(14) = 27.09$), so a Greenhouse-Geisser correction was applied ($\varepsilon = 0.55$). Tests of within-subjects effects show that the pattern ($F_{2.76,30.37} = 5.69$, $p < 0.01$) and the given angle ($F_{8,88} = 3.42$, $p < 0.01$) had a significant influence on this result. Post-hoc tests reveal that $P_{RH,IN}$, where 90.7% of sides were correctly identified, leads to significantly better results concerning recognition of correct side than $P_{DU,IN}$ ($p < 0.01$) and $P_{IN,IN}$ ($p < 0.01$). For $P_{IN,IN}$ this was mainly influenced by the bad recognition rates for small angles because of the confusion of vibrations, only 79.2% ($SE = 7.4$) of the directions on the left (30°) and 66.7% ($SE = 9.4$) on the right (330°) could be identified correctly. Looking at different angles, the only significant difference lies between the recognition of 60° (88.9%) and 135° (74.3%) to the left ($p < 0.01$). This indicates that in most cases the presentation of 60° led to an input on the correct left side, while when 135° was shown, more often inputs on, the wrong, right side occurred.

5.7.2 Recognition of distance

Accuracy of distance Overall, distance was inputted correctly in 78,2% of trials. In Figure 5.16 and Table 5.5, the different results for each pattern are presented. $P_{DU,IN}$ and $P_{DU,RH}$ performed

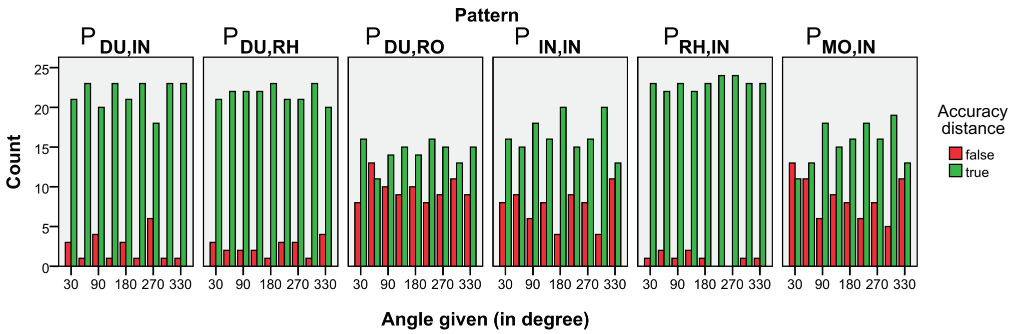


Figure 5.16 – Input of correct distance per pattern, split by angles

excellent as more than 90% of all distances were correctly recognized. $P_{RH,IN}$ provided even better results with a recognition rate above 95%. The analysis of variances shows that the main effect of pattern ($F_{5,55} = 9.73$, $p < 0.001$) significantly affected these differences. Post-hoc tests with Bonferroni correction for significance levels reveal that $P_{DU,IN}$ and $P_{RH,IN}$ caused significantly less errors concerning distance than $P_{MO,IN}$, $P_{DU,RO}$ and $P_{IN,IN}$ and [H3] (pattern influences distance recognition) can be confirmed.

The worst results of all patterns was achieved for $P_{DU,RO}$, where distance was coded with

	$P_{DU,IN}$	$P_{DU,RH}$	$P_{DU,RO}$	$P_{IN,IN}$	$P_{RH,IN}$	$P_{MO,IN}$	Overall
Correct distance	90.3%	90.3%	59.7%	69.0%	95.8%	64.4%	78.2%
Clear & understandable	3.82	4.55	3.09	3.36	4.09	3.36	3.71
Intuitive	4.00	4.27	3.18	3.55	4.00	3.36	3.73

Table 5.5 – Performance measures for recognition of distance. Subjective ratings were given on a scale from 1 = Strongly disagree to 5 = Strongly agree

roughness, with only 59.7% ($SE = 7.2$) of correct answers. This indicates that the rough and smooth signals used for the encoding of distance were not distinct enough. The main effect of distance was non-significant ($F_{1,11} < 1$), so none of the signals seems to be easier to understand than the other. This is supported by the subjective ratings for mental effort where only the second worst results with a mean of 3.96 (1 = very low, 5 = very high) could be reached. However, these

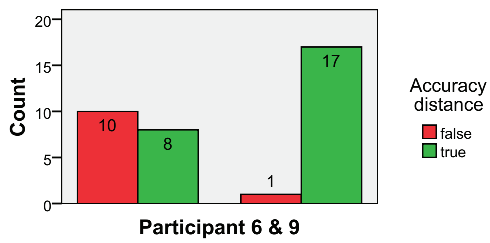


Figure 5.17 – Input of correct distance for two different participants ($P_{DU,RO}$)

results cannot be generalised for all participants. While some people commented after the tests they did not perceive any difference at all, others said the difference roughness levels were very easy to distinguish. The concrete results for two participants from each of these groups shown in Figure 5.17 illustrate this different ability to perceive the two levels. Since the navigation should be easy to understand not only for a certain group of people, this parameter should not be used to encode information anyway.

Influence of coding In Figure 5.18 it is shown how the coding of distance affected the recognition. Looking at the differences between coding with rhythm (a close turn is indicated by a double instead of a single pulse), intensity (more intense for a close turn) and roughness (rougher for a close turn), Mauchly's test indicated that the assumption of sphericity had been violated ($\chi^2(5) = 16.70$). Applying a Greenhouse-Geisser correction to correct the degrees of freedom ($\varepsilon = 0.68$), an ANOVA revealed that the coding significantly affected how well participants recognised distance ($F_{2.03,22.31} = 10.40$, $p < 001$). Rhythm achieved the best results with correctly identifying 90.3% of distances ($SE = 6.4$) compared to 59.7% ($SE = 7.2$) for roughness and 79.9% ($SE = 2.6$) for intensity. Intensity only achieved the second best result, however, it is used in four of six patterns. Filtering out the two patterns where direction is encoded with motion or change of intensity, because they already showed to achieve significantly worse results, the two remaining patterns are the ones where direction is only encoded with a longer or a double pulse. The performance of intensity becomes significantly better ($F_{1,11} = 42.70$, $p < 001$), highlighting the negative influence of the worse results. After this correction, the performance of intensity is with 93.1% ($SE = 2.1$) even slightly better compared to rhythm. When using intensity for indicating distance, participants often mentioned the metaphor *sound* that is also less intense when farther away.

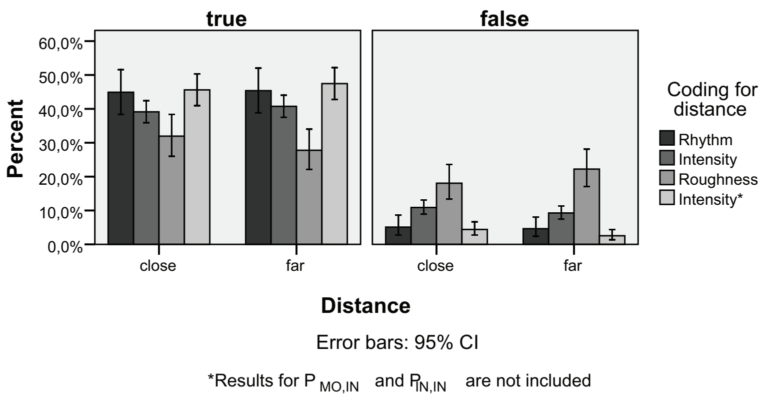


Figure 5.18 – Input of correct distance per coding

Clearness and intuition Table 5.5 shows the results from the subjective ratings collected after each pattern's test was completed. In contrast to the above finding where intensity showed to be useful to indicate distance, some participants had a general problem with some of the patterns where intensity was used. The signals for a close turn were always the same intensity level as the pulse for the current direction, while the vibration indicating a far turn was weaker. To distinguish between the "current" and "far" vibration they could rely on the change of intensity only, but if then a close turn was indicated they got confused because they could not easily associate the meaning to each of the vibrations.

Friedman's ANOVA was used to analyse the data in terms of significant differences. The ratings for clearness and intuition were significantly affected by the pattern they had just used

($\chi^2(5) = 21.26, p < 0.001$, $\chi^2(5) = 14.70, p < 0.05$). To follow up this finding, post-hoc tests were conducted. Significant differences concerning clearness were found between $P_{DU,RO}$ and $P_{DU,RH}$, indicating that changing the roughness level of a signal is less distinct than using a different number of pulses. The results for intuition show the same proportions, however, none of the pairwise comparisons turned out to be significant. This confirms observations made during the studies, where, for $P_{DU,RO}$, participants listened to the different signals more often in the introduction phase to get used to the differences, where they could repeat example vibrations as often as they wanted, before starting the training and test phase. The second-best rating after $P_{DU,RH}$ was achieved by $P_{RH,IN}$, confirming the best recognition rate of 95.8% . Only one participant commented afterwards that when a slight turn is shown and the pause between current and desired direction is small it is harder to tell if the signal is weak or intense.

5.7.3 Mental effort

Asked for their rating of the mental effort required in order to understand the encoded direction and distance for recently completed test, participants could choose between potential answers ranging from *very low* to *very high*. Excessive workload may result in lowered effectiveness [44] such as missing navigation information or misunderstanding a signal. Therefore, mental effort should be as low as possible to allow one to understand the presented information, even when navigation is only the secondary task besides, for example, taking care of traffic or having a conversation. Figure 5.19 shows the averaged ratings that were assigned to each pattern. The results

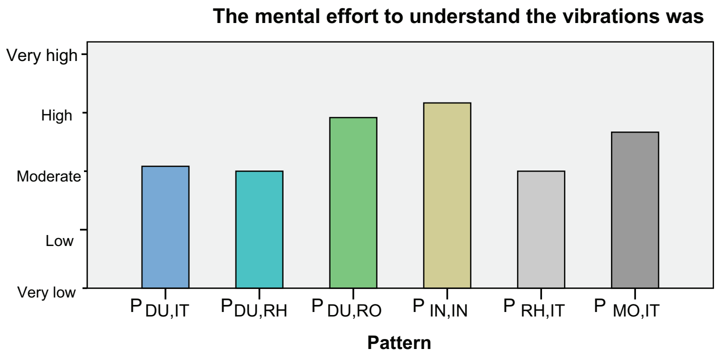


Figure 5.19 – Average rating of mental effort

indicate that $P_{DU,RO}$, $P_{IN,IN}$ and $P_{MO,IN}$ require a relatively high mental effort where $P_{DU,IN}$, $P_{DU,RH}$ and $P_{RH,IN}$ performed best. These ratings differ significantly regarding the pattern they describe ($\chi^2(5) = 29.14$, $p < 0.001$). Post-hoc tests with adjusted significance levels for pairwise comparisons reveal strong differences between the ratings. The pattern $P_{IN,IN}$ was found to cause a significantly higher effort needed to interpret the presented information than $P_{DU,RH}$ ($T = 2.46$) and $P_{RH,IN}$ ($T = 2.61$, $p < 0.01$), the last was also significantly better than $P_{DU,RO}$ ($T = 2.33$).

5.7.4 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*. This data was used to create an overall ranking by taking the best and worst rating per participant. Multiple patterns could be rated as best respectively worst. $P_{RH,IN}$ received the best rating for 8 out of 12 participants. $P_{DU,RH}$ and $P_{DU,IN}$ were perceived best by 7 and 4 participants, respectively. The other patterns achieved one or zero votes. As worst, 9 of the 12 participants rated $P_{IN,IN}$. $P_{DU,RO}$ and $P_{MO,IN}$ received five respectively three votes, the other patterns never achieved the worst result.

5.7.5 Input time

Another important criteria for the evaluation of different vibration pattern is the input time from the moment the *desired direction* is first indicated until a user finished the input. When this time is short, it is a sign for the signal being easy to understand and intuitive. For the analysis, input end values are taken (see Figure 5.8). Almost none of the participants made use of the possibility to correct the input, only if they unintentionally entered a wrong value and recognised it immediately they would click a second time. As starting point for this measure, the timestamp of the first

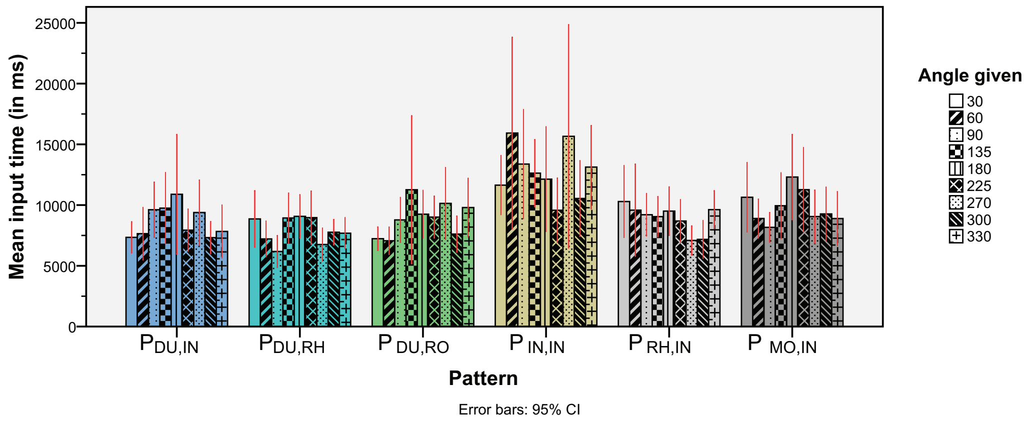


Figure 5.20 – Input time per pattern, split by angles

vibration for the desired, not the current, direction is chosen because this is the time the user could already know where to click. On average, participants took 9.49 seconds ($SD = 0.93$ seconds) until their last logged input. Figure 5.20 and Table 5.6 show the average input times per pattern. No significant influences of distance or angle could be observed. Mauchly's test violated the assumption of sphericity for the main effect of pattern ($\chi^2(14) = 53.82$), so a Greenhouse-Geisser correction was applied to correct the degrees of freedom. Results show that input time was significantly affected by the main effect of pattern ($F_{1.58,17.37} = 4.38$).
Two specific contrasts were chosen to reveal the influences of chosen pattern, that is to compare the lowest ($M = 7.94, SD = 0.67$) and highest ($M = 12.73, SD = 2.24$) mean with the means of the other levels. [H4], saying that the pattern has an influence on input time, can be confirmed, since simple contrasts revealed significant differences between the slowest pattern $P_{IN,IN}$ and $P_{DU,IN}$ ($F_{1,11} = 7.08$), $P_{DU,RH}$ ($F_{1,11} = 5.97$) and $P_{DU,RO}$ ($F_{1,11} = 5.57$), indicating that the input times for these three settings were significantly shorter. The second simple contrast concerning differences to the fastest pattern $P_{DU,RH}$ additionally shows a significant increase of time needed using $P_{MO,IN}$ ($F_{1,11} = 8.63$). The longest time needed was 12.73s when using $P_{IN,IN}$. Looking at the great confidence interval for 90° and 270° in Figure 5.20, it becomes clear that there were some outliers where participants had to feel the vibrations several times before making a decision. Moreover, comments point out that $P_{IN,IN}$ is more demanding than other pattern because you have listen to the complete signal and put it into the rotation context. A negative point was also that especially vibrations for sharp turns take much longer than the single pulses known from other patterns and it is hard to concentrate over the whole duration.

	$P_{DU,IN}$	$P_{DU,RH}$	$P_{DU,RO}$	$P_{IN,IN}$	$P_{RH,IN}$	$P_{MO,IN}$	Overall
Mean input time (in s)	8.63	7.94	8.91	12.73	8.82	9.82	9.49

Table 5.6 – Input times per pattern

5.7.6 Training effect

The importance to not only analyse experimental conditions such as vibrotactile parameters but also training effects for vibrational feedback on results has been mentioned in [61]. Van Erp and Van Veen who tested vibrotactile feedback in cars [23] concluded from feedback of participants that time and training is needed to *trust* tactile information. Hoggan and Brewster [39] show the results of trainings 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.
To check whether any training effects emerged during the user study, results are compared dependent on the order of test runs. Test 1 had no preceding test and therefore no training whereas when doing test 2 one test run had been accomplished before and so on. This can be seen as training even if the vibrations differ from pattern to pattern, the concept of imagining the rotation remains the same over all settings.

Recognition of direction Figure 5.21 shows how the input of the direction angle got more precise over time, from the first pattern the participants tested to the last. The mean deviation between indicated and reported direction improved from 53.32° in the first to 37.12° in the last run, a reduction of more than 30%. Pearson r for the correlation between order and deviation is -0.12, indicating that the more participants got used to the vibrations the smaller the error became. However, contrasts on the order term did not show a significant improvement of deviation over time ($p > 0.05$). A second analysis of variances was conducted to look for effects during each test run to see if there were any improvements from trial 1 to 18, but no significant trends could be identified.

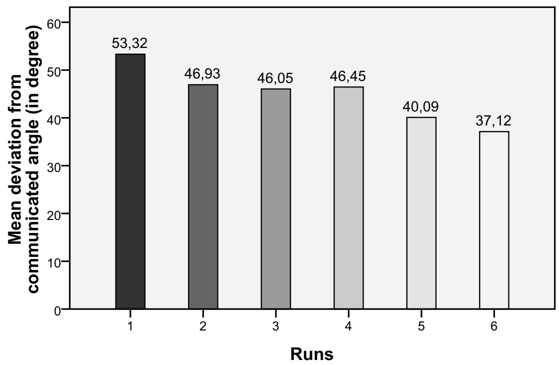


Figure 5.21 – Training effect on mean deviation from communicated value

Recognition of distance The performance of how well participants could perceive the displayed distance dependent on the order of the test runs did not change with increased training. The reason could be that the coding for distance changed from pattern to pattern. Even if in four out of six cases distance was coded with intensity the combination with other parameters caused each pattern to be perceived completely different from the others. A second analysis of variance testing the influence of training during trial 1-18 in a single test run also did not show significant results.

Input time For the average input time dependent on the order of execution no training effect is visible or statistically detectable ($p > 0.05$). Again the reason may be that participants had to learn a new set of vibrations every time and that this compensated for effects that could have emerged from repeated practice of the basic rotation. Also, no training effects within one test run could be discovered ($p > 0.05$).

5.7.7 Comments for patterns

$P_{DU,IN}$: Duration and Intensity Participants found this pattern easy to understand and the vibrations sufficient distinct. A common metaphor found was the comparison with sound that gets louder when one comes closer. However, after going through the tests some mentioned that when they did not concentrate they easily confused the signal for the current direction and the strong signal for the desired direction. It was considered as a drawback that the signals only varied in their duration, while intensity was the same.

$P_{DU,RH}$: Duration and Rhythm Asked if they had any metaphor or other aid for how to remember the different meanings for the signals, participants mentioned that the double pulse felt more immediate and such as a warning sign and that they could easily associate this with a close turn.

$P_{DU,RO}$: Duration and Roughness Two different metaphors for the meanings of different roughness levels were mentioned: on the one hand, roughness was equated with intensity and associated with the announcement for an upcoming event. On the other hand, roughness was compared to water, where the waves close to one standing in it are higher and get lower when far away.

$P_{IN,IN}$: Intensity and Intensity Overall, reactions after using this pattern showed that the concept is complicated, which is also supported by the worst result regarding the subjective ratings for needed mental effort, with a mean rating of 4.14 (1 = very low, 5 = very high). However, some participants highlighted that practicing helps a lot to perceive the different vibrations. One even underlined that he "really liked" it.

$P_{RH,IN}$: Rhythm and Intensity This pattern was rated best by most of the participants (multiple patterns could be rated as best). Comments highlight that the differences between the signals were very easy to perceive, so vibrations made up as combinations of rhythm (for direction) and intensity (for distance) on one vibrator seem to be most distinct. One participant, however, stated after the tests that he was sometimes irritated by all the vibrations because every rotation contains three and he could not always assign them to the correct direction.

$P_{MO,IN}$: Motion and Intensity Looking at the ratings of mental effort ($M = 3.79$), this pattern got the third-worst results. Comments revealed that this was mainly because the moving sensation did not help but irritate and the intensity levels for indicating distance were too close to each others. Moreover, according to one participant, the need to care about two different vibrators raised the overall effort.

5.8 Discussion

General observations Most participants looked concentrated at the screen during the test, at least in the beginning, and even leaned forward towards the screen to better feel the signs. In the end, some commented that they got the impression seeing the circle during the tests helped. Another behaviour that could be observed was that participants followed the imaginary rotation with the cursor. However, after some tests, some participants also looked away from the screen to perceive the vibrations. The background sound was said to be really distracting and that is causes the feeling of a realistic situation on the street. The next step is now to test system outside in a real environment and not while sitting in front of a laptop seeing the circle. Comments like *"I can **hear** the two different vibrations"* show that sensing the vibrations is compared to hearing, which lead to the finding that audio and tactile signals are perceived similarly, indicating the usefulness of designing interfaces crossmodally. Overall, the idea of using vibrations for conveying navigation information was found interesting. Several participants could imagine that it works outside while walking, and liked the idea of simple placing the device in the pocket. Moreover, one participant commented that it *"Can't beat visual map, but could be used complementary as a feature"*.

Choice of the best vibration pattern When looking at the recognition rates of distance, it becomes clear that for this coding, only intensity or rhythm should be used, because the other error rates lie over 25%. $P_{DU,IN}$, $P_{DU,RH}$ and $P_{RH,IN}$ therefore remain. Overall, $P_{DU,IN}$ achieved the second worst results regarding the mean deviation from the ideal input value for direction, so it is rejected, too. The results for *input on correct side* argue for $P_{RH,IN}$, where 85.6% of correct answers could be achieved, compared with 81.0% of $P_{DU,RH}$.
Moreover, rhythm seems to be useful for creating distinct vibrations, for both distance and direction (see Figure 5.18 and Figure 5.12). This parameter should therefore be used to communicate the more important information, namely direction, whereas for distance, intensity has proven to be easy to perceive, in combination with both one or two pulses for the desired direction.
It follows that $P_{RH,IN}$, where directions are distinguished by different numbers of pulses, and distance is indicated with changing intensity, will be used to conduct a further user study where the concept of the rotating radar is compared to other navigation systems.

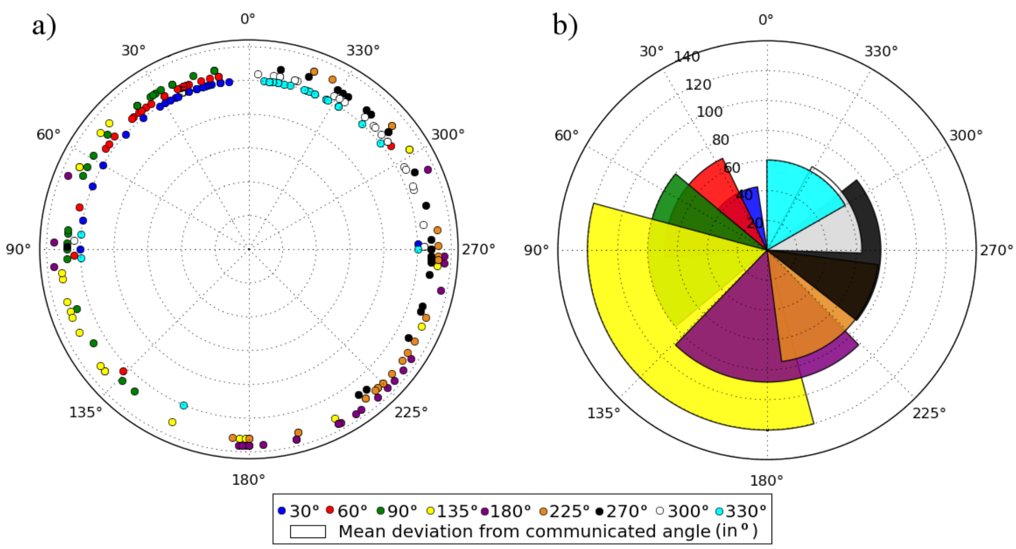


Figure 5.22 – a) Input distribution and b) average angle deviation for $P_{RH,IN}$

A closer look at the results for $P_{RH,IN}$ In Figure 5.22 a), the actual distribution of input values for the winner pattern $P_{RH,IN}$ is given. Those result in the mean deviations of the reported from the presented directions for the nine different angles tested, shown in Figure 5.22 b). The radius and height of the pies, or *recognition areas*, for each direction correspond to the mean deviation of the reported angle. For instance, the mean deviation of the angle 30° was 21.42°. This implies the high likeliness that the users perceive this angle in the interval 30° ± 21.4°. Therefore, the corresponding pie has a radius of 42.8 (2 x 21.4°). The reported angles for 30°, 60°, 300° and 330° are clustered around those angles in a), indicating that participants recognized the directions accurately with only slight deviations, which in turn leads to small pies in b). In contrast, reported

directions for 135°, 180° or 225° are spread over greater intervals in a) and corresponding pie slices in b) are of a bigger size. Directions around the back of the user (ranging from 135° to 225°) are recognised worse than directions in front. This might be due to the fact that there are longer interval durations between the vibrations 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. However, intervals between vibrations becoming shorter could make them harder to distinguish, and a raised amount of vibrations could disturb the user experience.
When recognition areas are overlapping and a direction in this interval is indicated, the wrong decision might be taken, leading to a navigation error. Figure 5.23 a)-c) shows different scenarios where NaviRadar provides enough accuracy. The red pie slices indicate the mean deviation for a given angle. Figure 5.23 d) shows a scenario where an error could occur easily. 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 5.23 e)). This leads to greater separation of the deviation areas as the direction "straight on" is distinctly indicated by a single pulse because the two indicated directions 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.

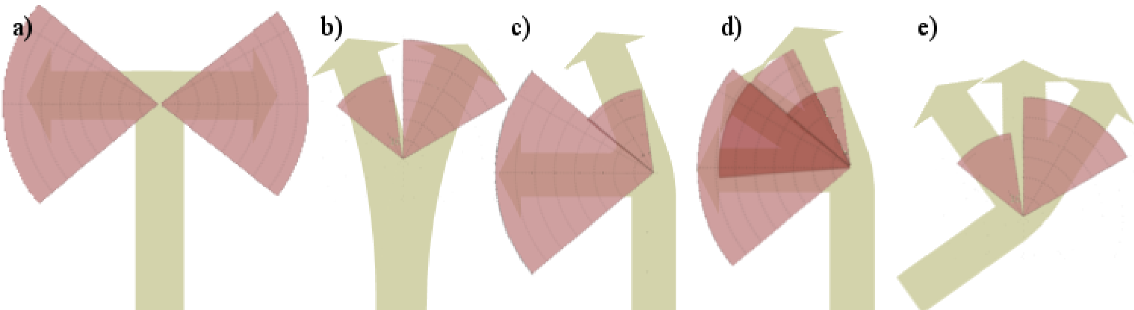


Figure 5.23 – Application of results to concrete crossing examples: a) 90° turn to the left and right b) Slight turns to the left and right c) A 90° and slight turn to the left d) Three turns to the left e) Shifted turns, now slightly left and right, and straight in front

5.9 Conclusion

The combination of rhythm and intensity in $P_{RH,IN}$ turned out to be the best of the tested solutions. For different combinations of turns, the recognition accuracy is sufficient, and complex situations improve when the user turns towards uncertain directions.
Moreover, a training effect on mean deviation incorporating all patterns was detected (see Figure 5.21) from 54.32° in the first to 37.12° in the last run, a reduction of more than 30%. With a mean deviation over all runs of 37.45° for the winner pattern $P_{RH,IN}$ (instead of 44.99° for all patterns), these results indicate that even better values can be achieved, but due to the low number of participants, no statistical evidence can be produced for this idea. However, the overall trend underlines the importance of sufficient training, so for further studies, more training runs and advanced feedback such as always showing the correct direction after inputting to allow constant improvement over runs, should be provided.
This study was carried out in a controlled laboratory setting and no real navigation task had to be executed. In a next step, the results now have to be put in a realistic context to see if the concept also works while walking outdoors.

6 Outdoor study: Testing in a realistic setting

An outdoor study was conducted to test the concept of NaviRadar in a realistic setting and compare it with two other navigation systems. One of those also uses vibrations on a mobile phone, but with a different signalling concept, while the other one gives audio instructions like most commercial navigation systems, where a short vibration announces an instruction. All three systems do not provide any visual output, but users have to rely on other perceptional channels, and can use their vision to observe the surrounding and take care of traffic or obstacles in their way. This section first gives details about the compared systems and the study design, before summing up the test results. Further ideas for improvements are given at the end of the section.

6.1 Navigation systems

In the following, the different compared navigation systems used in the user study are described in detail.

NaviRadar The pattern used in the comparative study was chosen because of the results of the preliminary study (see Figure 6.1). A regular short vibration is presented that indicates the direction one is heading to, while a double-pulsed vibration shows the desired direction. The intensity of this last vibration indicates the distance to the crossing.
As threshold between the different indications of the desired direction, 15 and 30 metres were chosen. If the distance to the turn is less than 15 metres, the direction is indicated intensely. This distance is taken after experiments with commercial pedestrian navigation systems like Ovi maps, that tell the user to turn *"now"* at about that distance. Between 15 and 30 meters, the direction was indicated weakly to allow the user to prepare for the turn, this value was chosen to provide each intensity level for about the same time. If the distance was more than 30 metres, only the vibration for the current direction was presented, indicating that no turn is required. Figure 6.2 gives an overview over the timing of vibration patterns. When no turn is coming up, the regular

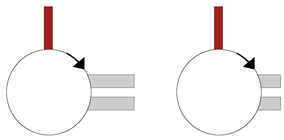


Figure 6.1 – Schematic view of the vibration pattern $P_{RH,IN}$ for NaviRadar

one pulsed heartbeat is indicated to maintain the feeling for the vibration and as a confirmation that the system is still alive. When the user is approaching a waypoint where a turn has to be performed, the system starts to indicate the direction with a low intensity. At the next threshold, the intensity becomes strong to show that the next turn is the one to be taken. As soon as the user changes his direction, the feedback is adapted automatically. As soon as the user has passed the waypoint and is heading towards the waypoint, the heartbeat indication starts again.

PocketNavigator The PocketNavigator is a map-based pedestrian navigation application available in the Android market since spring 2010, already introduced in Chapter 3.6.1. Navigation information is given on the one hand in form of a map where the current route is indicated as a gray line, like shown in Figure 6.3 a) and b), and an arrow in the lower left corner indicates the current direction. On the other hand, turn-by-turn instructions are transmitted by vibrations. The user is, similar like with a compass, always guided to the next waypoint. For this purpose, respective vibration patterns are played. A screenshot of the application's introduction showing the different pattern is displayed in Figure 6.3 c). The presented vibration patterns always contain two pulses

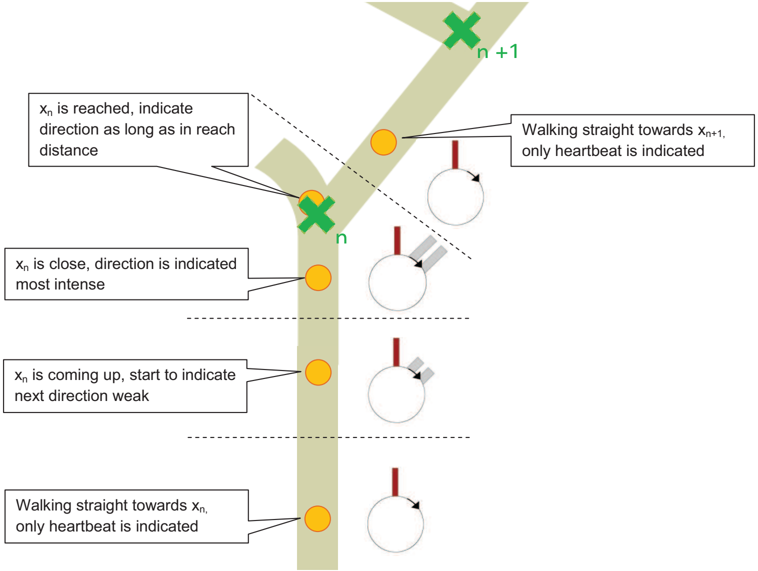


Figure 6.2 – Navigation concept for NaviRadar

Figure 6.3 – Screenshots of the PocketNavigator: a) Start screen b) After selection of a route c) Introduction of vibration pattern

(see Figure 6.4 for an example). As long as these two are both short it means that one is going straight towards the next point to turn. Assuming that a slight left turn is required to reach the next point, the first vibration is longer, and the longer it gets the more one would have to turn around. On the other hand if a right turn is indicated by an extended second vibration. An exception is the special signal for an angle around 180° or "turn around". It stands out as it contains three short pulses and since it breaks with the rhythm of two pulses it appears to be very obtrusive. The guidance always refers to the current position and heading of the user, and the feedback is adapted according to the user's behaviour. To determine the location, GPS signals are used. The current heading is obtained in two different ways, depending on the device's mode. When the device is held in *scanning mode*, that means tilt and roll angles are less than 20° to one side, the internal compass of the phone is used. This orientation can only be achieved when the phone is held in the hand, and normally not when the phone is put in one's pocket. In this case, GPS measurements are used to obtain the current heading by taking the direction between the last tracked points as the direction the user is currently headed in. As this method only works as long as the user is moving, this is called *walking mode*. When the phone is in twisted orientation and the user stopped walking, it is not possible to obtain the current heading and the feedback is muted.

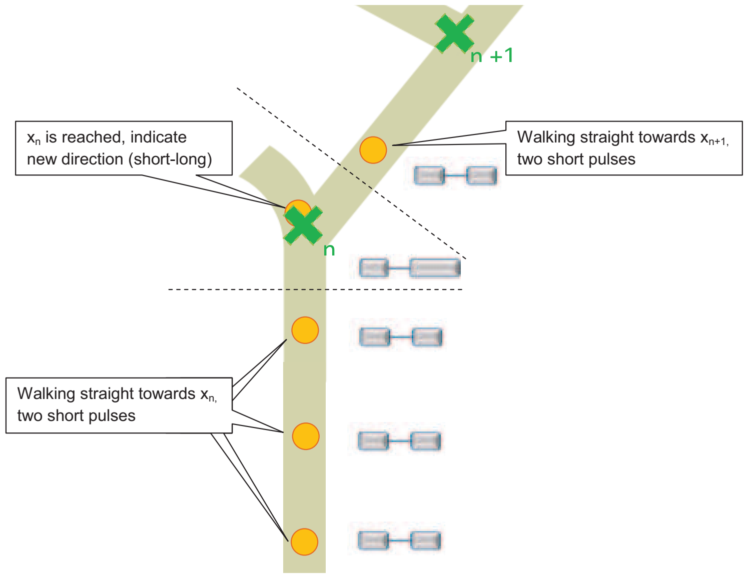


Figure 6.4 – Navigation concept for the PocketNavigator

The frequency of the feedback provided is dependent on the current mode. In *walking mode*, the direction is indicated about every 5.0 seconds, while in *scanning mode* every 1.5 seconds a new vibration pattern is started. This is useful when the user searches for the next waypoint by pointing into different directions, and also for learning the idea behind. As soon as one comes into a range of about 5 metres of the currently indicated waypoint, it is regarded as reached and the user is guided to the next waypoint.

Ovi Maps The second navigation system used in the comparative study was the newest version 3.04 of Ovi Maps. This further developed version of Nokia Maps is available for free since January 2010 [74] on the latest generation of Nokia phones. It offers a wide range of functions regarding map based navigation, including turn-by-turn instructions for cars as well as pedestrians. A screenshot of the running application is shown in Figure 6.5, where the current route is

Figure 6.5 – Screenshot of Ovi Maps

indicated as a blue line on the map, and the current trace of GPS measurements is shown as red dots that fade out after a while. One specific navigation mode offers the possibility to use speech instruction that are preceded with a vibration. In this combination, the user is informed via a short vibration that spoken instructions (e.g. "turn left in 50 metres") will follow soon. In response, the user can then bring the phone to their ear like when calling someone, in order to hear the spoken instructions more clearly. They can listen to the instruction at a volume that other people are not disturbed but does not have to wear headphones. Figure 6.6 shows example instructions given during a route.

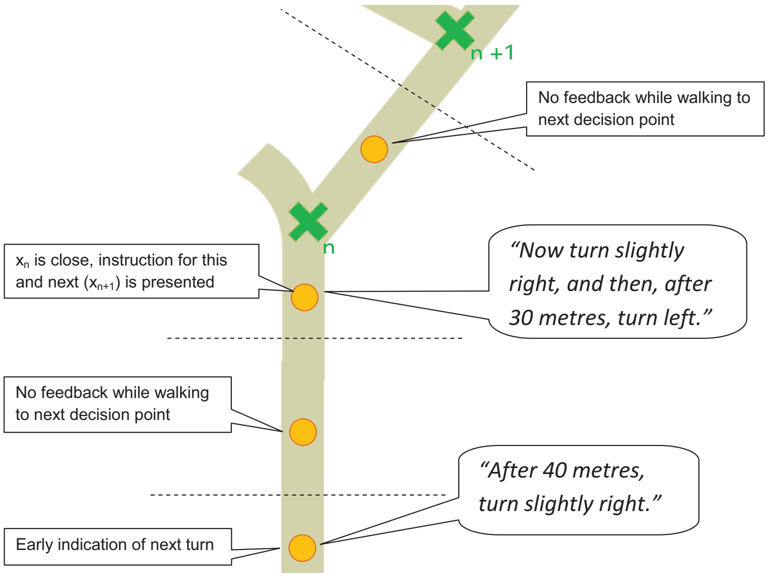


Figure 6.6 – Navigation concept for the AudioGuide

6.2 Prototype

For the comparative study all three navigation systems introduced in Chapter 6.1 have been implemented to run from one application. This was done to guarantee that the only difference between the systems exist in the way navigation information was presented, and not in the underlying routing data or the tracking quality. Moreover, performance data could be logged which would not have been possible from a third-party application. As the mobile phone screen was not used during the study, none of the visual aspects of those systems have been implemented.

6.2.1 Software

Two applications were developed for the second study: one is similar to the test application of the first study and is used for the introduction and training of navigation systems. The other one is used for the navigation task (see Figure 6.7 for an overview).

Navigation Besides presenting navigation instructions to the user via the respective channels, the main application incorporates context sensing. Therefore, overall 6721 lines of Java code, and 2575 lines of XML code have been written. Two main activities are used: `StartActivity` is used to set the configuration for a test run, namely the IDs for participant, system, and route. `NaviRadar` is the main activity, controlling the feedback by getting the results of the different sensors. Figure 6.8 a+b) show screenshots of the start screen, and what users saw during the study (a black screen). Screenshots c+d) show how the application could be debugged during the study. One menu option was to show the current state, and then compass and location data could be checked. If a restart during a run was required, the already walk way could be simulated by inputting positions directly on the map.

All positioning data obtained on the way is logged and saved to a database, and as XML file to the sd card. Ways contained in the local database can be viewed with the `WayViewer`, and files from the sd card can be imported to the database using the activity `Importer`. The XML schema and all screenshots can be found in Appendix B.

Context sensing Positioning of the users is realised by using GPS measurements of the built-in GPS unit. By computing the distances between the current position and the next and last route

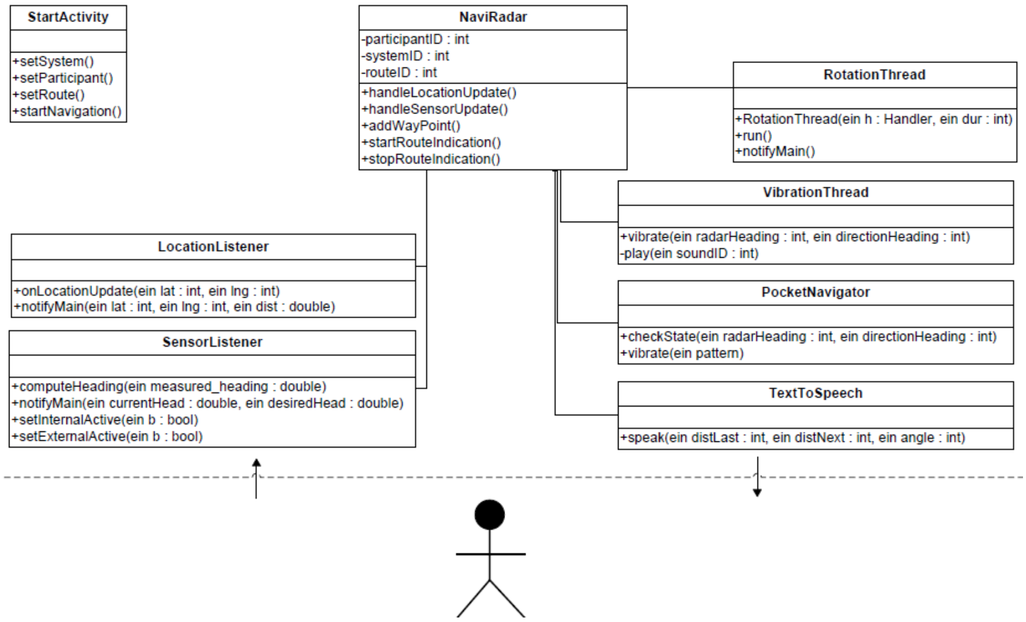


Figure 6.7 – Outdoor study: Class diagram for prototype application

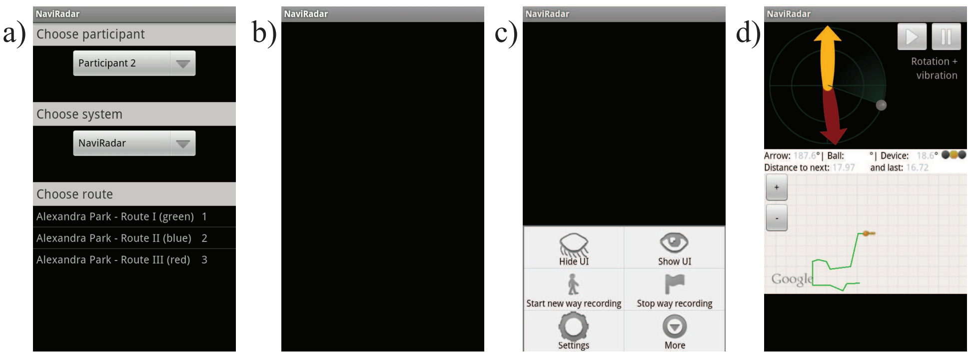


Figure 6.8 – Outdoor study: Screenshots of navigation application. a) Start screen b) Black screen during the user study c) Debug menu d) Debug screen

point, the timing of navigation commands can be determined. However, since GPS measurements show a large variance from one run to the other, depending especially on the weather, which causes problems with the recognition of the current position, an improvement is applied by snapping the measured GSP points to the route data. This technique is already used by car navigation systems were it is called *map matching* and a measurement is always snapped to the nearest street [67]. Here, measurements are directly mapped to the current route as during the study, participants will never be in the wrong street, but are guided back when navigation errors occur. Figure 6.9 shows the different variants. Snapping also avoided that measured waypoints are associated with the wrong position on the route. The example data of route II) shows that the positions of different parts of the route could be confused, and a whole part of the route would be missed out. The current heading is obtained by either using the external (NaviRadar, via Bluetooth) or internal (PocketNavigator) compass. A median filter using the latest nine values is applied, where the compasses are set to an output rate of 10 Hz. With every new measurement, `computeHeading(double measured_heading)` is called, that preprocesses the measurement according to the navigation system and the distance to the last and next to reach route point. The

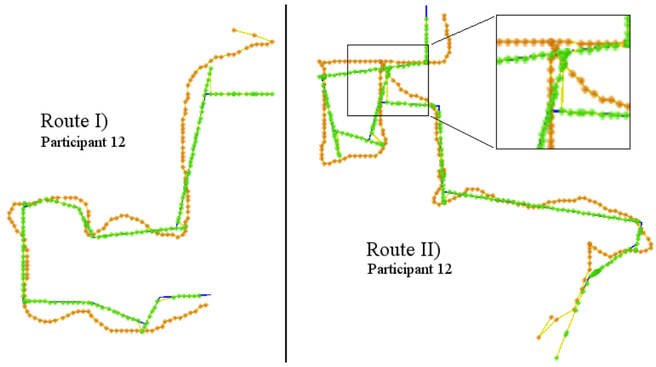


Figure 6.9 – Prototype: Snapping of GPS measurements. Real GPS measurements are shown in orange, snapped points to the route in green, the underlying route in blue.

result, the difference between current and desired heading (negative if going too far right, positive if going too far left) is sent to the main activity that initiates the resulting feedback.

Output Depending on the chosen navigation system, the output was created in a different way. Using NaviRadar, a background thread is giving a regular clock pulse 360 times in three seconds corresponding to the radar rotation. Every time, it is checked if the virtual radar coincides with one of the directions to be indicated, and which audio file has to be played to create a vibration, like in the prototype of the first study, depending on the kind of direction and now also the dynamic measured distance to the last and next to reach route point.
Using the PocketNavigator, a background thread manages the timing of signals, depending on the current orientation of the device (flat: 1.5 seconds, twisted: 5 seconds). Then, current and desired direction are compared to identify the pattern of the TwoPulse set to be played, and the corresponding call of `vibrate(float[] pattern)` is performed.
Using the AudioGuide, the current distance to the next route point is checked ten times per second, and depending on whether the last route point has already been passed and the next turn has already been indicated, a vibration is created with `vibrate(float[] pattern)` and `speak(String text, int queueMode, HashMap<String, String> params)` is called on the preloaded `TextToSpeech` object.

Training The training application, which introduces the different systems to the participants before actually using them while walking, was similar to the application used in the preliminary study. It was extended to also introduce the two new systems PocketNavigator and AudioGuide (see Figure 6.10 and 5.1 (page 47) for screenshots). The part for the PocketNavigator was kept similar to the old structure: participants were first introduced to the different vibration pattern (with tests and graphics based on the original application), then had nine training inputs, before testing all angles. The AudioGuide introduction, in contrast, was kept very short and only gave some example instructions. The introduction to NaviRadar was almost the same as before, except participants were shown the encoding of distance only in the end after performing the training tests to be able to compare the results with those from PocketNavigator where no distance is encoded.

6.2.2 Hardware

The study was conducted with a Motorola Milestone running on Android 2.1. The output means such as audio output, creating vibrations (see Chapter 4.1.2) and text to speech are supported by the operating system. As the first study identified the optimal tactons using the C2 tactor, it was used once more for the comparative study. Unfortunately, the tactor is strongly magnetic

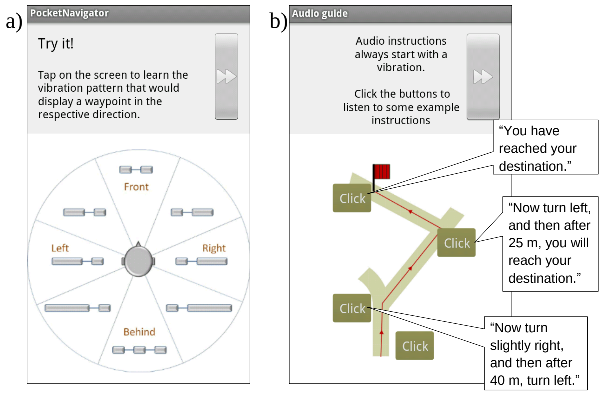


Figure 6.10 – Outdoor study: Screenshots of introduction for a) PocketNavigator and b) AudioGuide

and heavily influenced the built-in compass when attached to the backside. Accordingly, the external compass described in Chapter 2.5.4 was used, and a special holder was built to provide a

Figure 6.11 – Distance holder for prototype

sufficient distance between tactor and compass. It is made of a commercial tiltable phone holder by Brodit [121], which is mounted onto a self-made transparent acrylic spacer. Its length was determined by examining the outputs of the compass with the phone and other electronic devices used in the study later at different distances, and was set to 32 cm. To make it more comfortable to hold, additional 2 cm of space was added between the actual holder of the phone and the beginning of the big spacer. Figure 6.11 shows the whole device and how it is held. The C2 tactor and amplifier already used in the preliminary study were attached to the holder as well.

6.3 Study settings

The study was conducted outside. The chosen area of Alexandra Park was already used by Rukzio et al. [80] in a similar study. It is a part of the Lancaster University campus occupied with student houses and consists of a lot of small streets and paths so that many turns could be included into routes with reasonable lengths. Figure 6.12 shows the three routes designed for the user study. Moreover, most of the streets are pedestrian ways where no cars are able or allowed to drive on,

Figure 6.12 – Routes I)-III) in Alexandra Park

so the risks of accidents was minimised as much as possible. The mean route length was 380 m, distances between the single waypoints range from 15 to 110 m. Further details of the routes are presented in Table 6.1.

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
III)	6	4	10 (+3)	370 m

Table 6.1 – Characteristics of tested routes

6.4 Participants

Twelve participants, six female and six male, took part in the study. None of them had been participating in the previous study. As for the first study, they were recruited through posters distributed around campus of Lancaster University. Participants from a wide range of disciplines were selected. Their age ranged from 19 to 51 with a mean age of 28.25 ($SD = 10.01$). One of the participants was left-handed. All participants except one used their dominant hand to hold the phone, only one right handed person used his left hand because he held an umbrella with his right one.

Participants rated themselves as highly experienced with computers ($M = 4.25$, $SD = 0.45$ on a scale from 1=None to 5=Expert) and mobile phones ($M = 3.83$, $SD = 0.83$). Only 4 out of 12 indicated a high experience with car navigation systems ($M = 2.50$, $SD = 1.45$). All of them had experiences with pedestrian navigation in terms of using paper maps or tourist guides ($M = 3.08$, $SD = 0.90$) and half of them had used electronic devices for pedestrian navigation before ($M = 2.00$, $SD = 1.13$). All except one participant had experience with some form of vibration feedback such as the vibration alarm when a mobile phone is in silent mode (92%), game controllers with vibration feedback (67%) or vibrations as touchscreen enhancement (58%). 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.

6.5 Experimental design

As in the preliminary study, a within-subjects repeated measures design was chosen. Participants had to test all different systems to be able to compare them afterwards. The study design as well as the questionnaires follow a similar study comparing pedestrian navigation systems by Rukzio et al. [80].

Independent variables The independent variable *Navigation system* contained three levels, according to the systems presented in Chapter 6.1: NaviRadar, PocketNavigator and AudioGuide. The order of those systems was counterbalanced over the participants by using a $3x3$ Latin square (see Figure 6.13) resulting in six possible combinations. Each of these was conducted with both a male and a female participant. The order of the routes was always the same (I $\rightarrow$ II $\rightarrow$ III), so that overall, each navigation system was tested four times on each route.

$$\begin{pmatrix} A & B & C \\ A & C & B \\ B & A & C \\ B & C & A \\ C & A & B \\ C & B & A \end{pmatrix}$$

Figure 6.13 – $3x3$ Latin square design

Dependent measures For the main comparison of the performance of the three navigation systems, error and disorientation events were counted during walking. After each run, participants were asked for their rating of different subjective questions. After all runs were completed, a comparison of all systems was performed. For the questionnaires, see Appendix B.
The main measurements taken during the training phases of NaviRadar and PocketNavigator are like in the first study absolute input, deviation of perceived from presented direction, and the time between start of indication and end of input.

6.6 Procedure

Participants took part in the study individually. In the beginning, they were introduced in the purpose of the study, the comparison of different pedestrian navigation techniques. They were not told which technique was the one developed in this thesis, but were left thinking that all three are self-designed to avoid biased ratings. They signed a consent form, and the researcher led them to the starting point of the first route. There, they were introduced into the first navigation technique. In the case of the AudioGuide, they were presented some sample instructions, for the tactile approaches, a more sophisticated training was needed. Here, participants were explained the concept and then presented 18 directions (similar to the first study) where they had to indicate where they would travel using a circle on the phone. Nine directions were presented to ensure they understood the system. A further nine directions were used to compare the performances (see Chapter 6.7.6). Participants were allowed to ask questions throughout the experiment.
Each participant experienced the test routes in the same order (I $\rightarrow$ II $\rightarrow$ III). They were instructed to walk with their normal walking speed where 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 metres. 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 system, and could provide additional comments. After all three routes had been completed, another further questionnaire was filled in that contained questions about demographics, as well as a comparison and ranking of all three systems.
Additionally, comments and exceptional behaviour were collected during the study. Once the study was complete (circa 60-70 minutes from its commencement), participants received a compensation of £10 and were asked to sign a participant payment form.

6.7 Results

The next section reports the results gained from the comparative user study. Unless otherwise stated, all effects will be reported at a .05 level of significance.

6.7.1 Limitations

An important issue during the conduction of the user study was the inaccuracy of GPS measurements which have been negatively influenced by the proximity of nearby buildings, as already experiences by other researchers [97] [45] [37]. Several tests had been run before the study to decide on the best placement of route points so that instructions are provided at the correct time. However, as shown in Figure 6.14, traces from the tests are widely spread around the original

Figure 6.14 – Diversity of tracked ways for Route I)

way. This led to problems with the timing of commands and even incorrect indications. Incorrect indications were logged during walking and by analysing the videos taken during the study, the behaviour 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 were 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, like already experienced in compass tests (see Chapter 2.5.4). When this occurred, the compasses required recalibration.
Moreover, task completion time were not examined, since times are distorted by confusions due to 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 [80].

6.7.2 Errors and disorientation events

The study results show that all three navigation techniques could be effectively used for navigation. Overall, only few errors, like shown in Figure 6.15, occurred during navigating with each of the navigation systems, where overall 294 turns are included in the analysis. An error occurred when a participant travelled in the incorrect direction for more than 5 metres. He was then stopped by the experimenter and redirected back to the correct route. NaviRadar and AudioGuide 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 metres when the instruction "In 45 metres, turn left" had been given. Disorientation events occurred four times

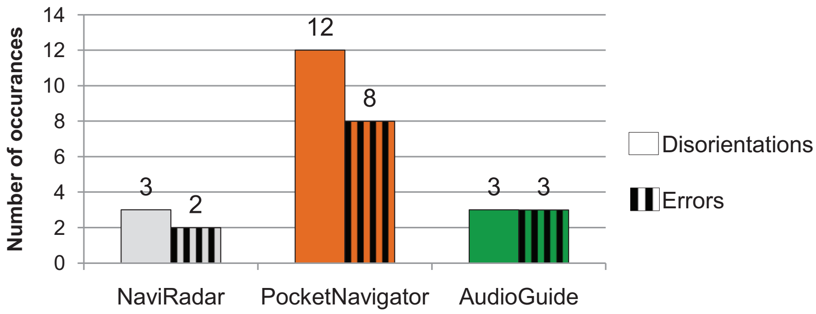


Figure 6.15 – Overall count of errors and disorientations for all participants

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 (see Figure 6.16). . 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.

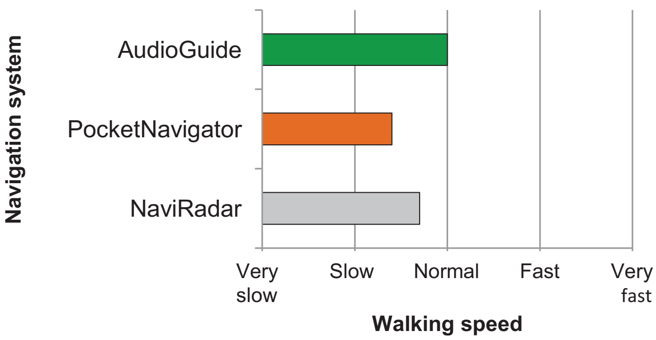


Figure 6.16 – Subjective rating of walking speed

6.7.3 Usability satisfaction

After each test, participants were asked to rate different aspects of the navigation system by agreeing or disagreeing with different statements, taken from the IBM Computer Usability Satisfaction Questionnaire [54]. An overview over the results is given in Figure 6.17. All three approaches show positive results. Friedman's ANOVA was used to analyse the data in terms of significant differences. A significant influence of the used navigation system could be detected for all ratings

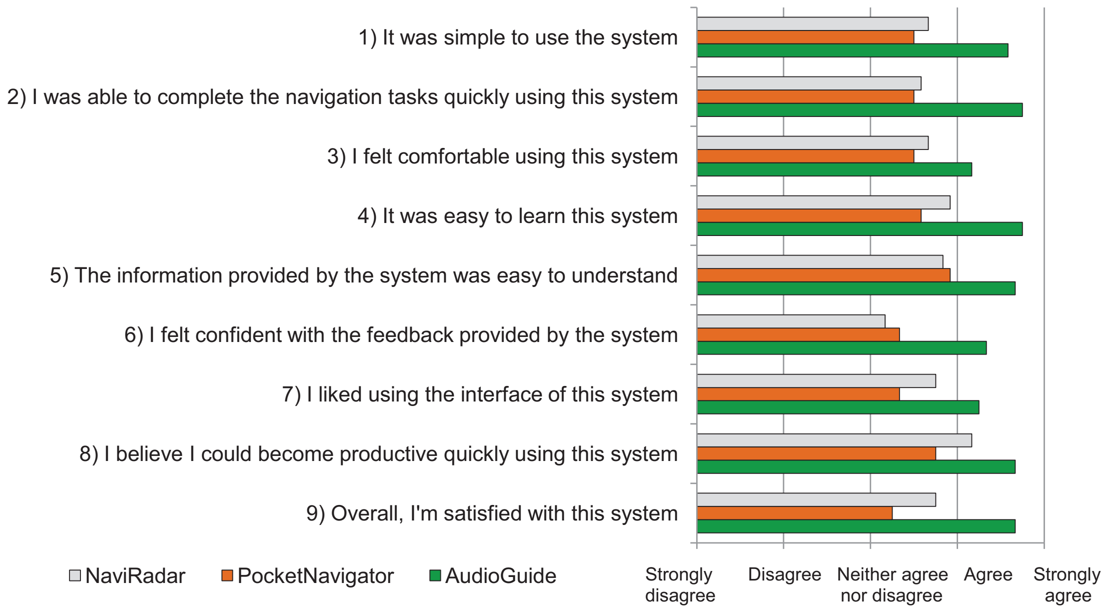


Figure 6.17 – Subjective usability

except when asking for statement 3 (feeling comfortable) and 7 (like using the interface). Pairwise comparisons using Wilcoxon tests were conducted to follow up these findings. Bonferroni corrections were applied and so all effects are reported at a 0.016 level of significance.
No differences could be detected for statements 5 (information was easy to understand), 6 (feeling confident with the feedback), and 8 (become productive quickly). All others revealed significant better ratings for the AudioGuide than for the PocketNavigator. It appeared to be easier to use (1) and to learn (4), tasks could be completed more quickly (2) and an overall higher level of satisfaction could be created (9).
No significant differences in the ratings of NaviRadar could be detected for any statement, suggesting that it did not affect the ratings negatively compared to the AudioGuide, but also not positively compared to the PocketNavigator.

6.7.4 Workload

The results of the selected questions of the NASA Task Load Index [36] are depicted in Figure 6.18 and show the mean results of all participants. Frustration level was described in the questionnaire as *How insecure, discouraged, irritated, stressed or annoyed did you feel during the task?* Effort was described as *How hard did you have to work (mentally and physically) to accomplish your level of performance?* Mental demand was described as *How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)?*.
A low to very low task load can be shown for the AudioGuide, an neutral to low task load for the other two. Friedman's ANOVA was used to analyse the data in terms of significant differences. Pairwise comparisons using Wilcoxon tests were conducted to follow up these findings. Bonfer-

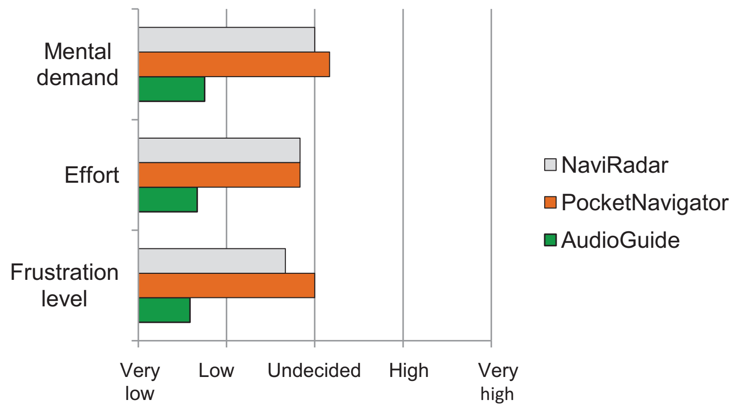


Figure 6.18 – Subjective ratings of workload

roni corrections were applied and so all effects are reported at a 0.016 level of significance.
For the ratings of mental demand, a significant influence of used system ($\chi^2(2) = 12.51$) can be stated. The AudioGuide achieved significantly better results than both other systems. This might be because audio instructions can be understood without thinking, while feeling vibrations requires to associate the meaning, at least when the systems are used for the first time and therefore only little training how to interpret the signals had occurred. In contrast, one participant said overall mental demand can be reduced when permanent feedback like given by the tactile interfaces is available, as it is less important when an instruction is missed because it can be heard or felt again when the user is ready for it. Moreover, mental demand for the AudioGuide was said to be slightly raised by the fact that judging of distances and matching them to the actual street layout was not always easy.
Regarding effort needed to use a respective system, again a significant influence of the used system ($\chi^2(2) = 13.19$) was observed, with the AudioGuide performing better than the other two systems. Effort with AudioGuide is very low because listening to instructions and mapping left and right to the street layout is a task that is frequently performed. However, one participant said for her it causes a higher effort to interpret left and right than relying on the direction indicated by vibrations.
The perceived frustration level was also significantly influenced by the used system ($\chi^2(2) = 10.29$). This time, follow-up tests only showed a significant difference between AudioGuide and PocketNavigator. The raised level of the latter emerged from having to slow down or stop at crossings to receive a new direction indication.

6.7.5 Preferences and comments

After completing all three test runs, and therefore with experience in the practical usage of all three systems, participants were asked for their preferences and further comments for the three systems (see Figure 6.19). The AudioGuide received on average place of 1.3, NaviRadar 2.25 and PocketNavigator 2.4.
The main reason why audio instructions were preferred was the fact that it is easy to learn and does not really need any training, participants were only presented some example instructions to know what they would sound like. However, the other two systems seemed to be more accurate and to have more potential, because the feedback is continuous and dynamically adapted to the current heading. Moreover, several participants mentioned the drawback of audio instructions compared to vibrations that they only work for people who understand the language and are used to the units of measurements, like one participant asked if the instructions given in metre could

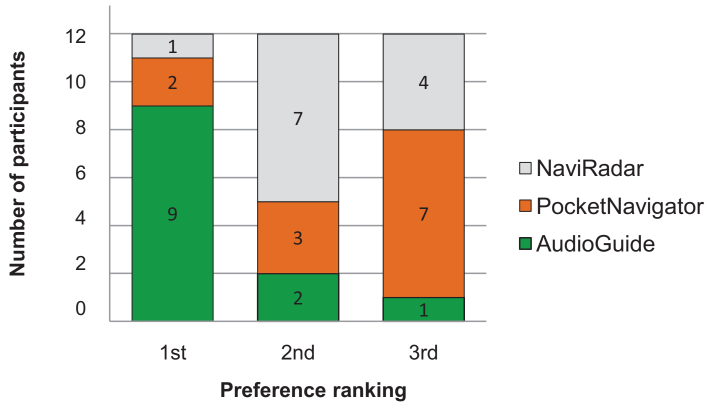


Figure 6.19 – Preference rankings, obtained after all runs were completed

be switched to yard. Two participants found it easier to learn the concept of the PocketNavigator, but NaviRadar was said to feel more accurate, even than the audio instructions, and made the participants feel more confident. The indication in advance was seen as an important advantage of both AudioGuide and NaviRadar.

NaviRadar Participants were surprised how good they could navigate with NaviRadar since it needed some trials to understand the idea behind it. After the introduction and when they had built up the radar metaphor, they got used to it easily and liked the unobtrusive, short signals, that were said to be perceived like shoulder taps. With the mental picture of the radar, one participants commented that feeling the direction is intuitive, another one even started chatting with the researcher during the test run. One participant explicitly mentioned the possibility that visually impaired people could be advantaged to use the system, since they have a good trained sense of touch. Another positive aspect was the applicability for terrains where no paths are available but where the signal could give the overall direction to the destination which is hardly possible with an audio guidance.
Problems that occurred were mainly caused by the indication of small angles where participants had problems to distinguish between slight left or slight right turns (double-single or single-double pulse). On the other hand, the slighter the angle that was presented, the easier it seemed to be to estimate the timing of the two distinct vibrations. At least in the beginning, participants had to concentrate on the signals to understand the meaning. A feature several participants would like to have included is a confirmation of a successful turn. By now, this was only implicitly given by not indicating the direction anymore after a turn had been completed.

PocketNavigator Like with NaviRadar, participants needed some training to learn the meaning behind the vibrations used by the PocketNavigator, however, after that, it felt easy to use. The scanning feature was said to be useful, and again, the possibility to use it to indicate an overall destination was mentioned. The immediately adapted feedback helped to confirm a completed turn.
Comments regarding the distinguishability of signals varied. While some participants found it easy to distinguish between a slight and sharp turn to one side, others had problems estimating the different lengths. One participants even had problems determining the longer one of two vibrations and needed some extra training directions to get used to it. One criticised that the coding had no further meaning and had to be learned by heart, while another participants found it "clever". It was commented that the signals did not become intuitive but had to be actively felt and even that it was necessary to slow down to understand the meaning, and that it distracts a lot. The

provided accuracy was also seen as a drawback since only three different directions per side could be indicated, and the difference was only easy to feel when presented after each other.
During the test runs, participants mostly held the phone in front of them to enable the scanning mode because the walking mode was influenced too much by the inaccurate GPS measurements, and two participants said they would probably be more aware of the feedback when carrying it in their pocket. Using the compass also revealed that the feedback is too sensitive to the measured direction. Especially for the front angle, the range of 45° is too small, so it often happened that single wrong vibrations were played.
The concept of the PocketNavigator does not involve giving the next direction in advance but only as soon as the previous waypoint had been reached. Because of the varying GPS accuracy, the exact position where the feedback is given, varies, so most of the times it was given at a crossing, but it also happened that the signal to the next waypoint was played some metres in advance of a crossing, and participants took it as an immediate instruction and took abbreviations over grassland. This indicates that they were so concentrated on the signal that they did not care about walking on paths anymore, which could lead to dangerous situations if that for instance occurred when crossing a street.

AudioGuide The AudioGuide was said to be the system the easiest to learn without concentrating on vibrational feedback, while the alerting vibration in the beginning of each instruction was seen as very useful to be able to then hold the phone closer to the ear to better understand the instructions. Participants started chatting with the researcher during the tests like with NaviRadar indicating that they were not too concentrated on getting the navigation information, however, as soon as a instruction was given the chat had to interrupted to be able to understand the command. Being told to go left and right was commented to be more familiar and "human" than being indicated a direction with vibrations. The fact that someone was talking to give the navigation information was seen to add interactivity to the task, even if it did not because there was no possibility included to actively scan or ask for feedback. A further positive aspect was that participants did not have to be focused on feeling vibrations all the time.
Several participants mentioned that it would be a problem to use this system in a noisy environment, and that it is not possible to have it in the pocket while using it, except with wearing headphones which were acceptable for some participants but not for all. A further drawback is the missing constant feedback, and that it would be a problem if a instruction is missed as there is no easy way to have it repeated, only something like a special button to replay. Moreover, there is no confirmation that the current direction is correct, which could be realised by a repeated *"keep track"* command. It was also commented that this system does not work on an open field as it relies too much on given paths.
Overall, this system is the one that is least dependent on the accuracy of GPS signals, since it gives feedback only when certain thresholds (distance to next crossing) are reached, not all the time. With the feature that not only the next turn but also the one after it are indicated, it makes it possible to even perform a turn when the corresponding instruction is missed or left out.

6.7.6 Comparison between NaviRadar and PocketNavigator

As an introduction to the concepts and training to get used to them before actually using them for navigating on the routes, a similar test application like in the preliminary study was used for NaviRadar and PocketNavigator. Participants were presented different directions and had to input them on a circle, for instance the direction of nine o'clock for indicating a 90° left turn. In the following, the results from these tests are used to compare the performance of the two navigation systems.

Absolute input Figure 6.20 shows what participants thought they were presented for nine different directions. The results from using the PocketNavigator show a surprising trend. Since the

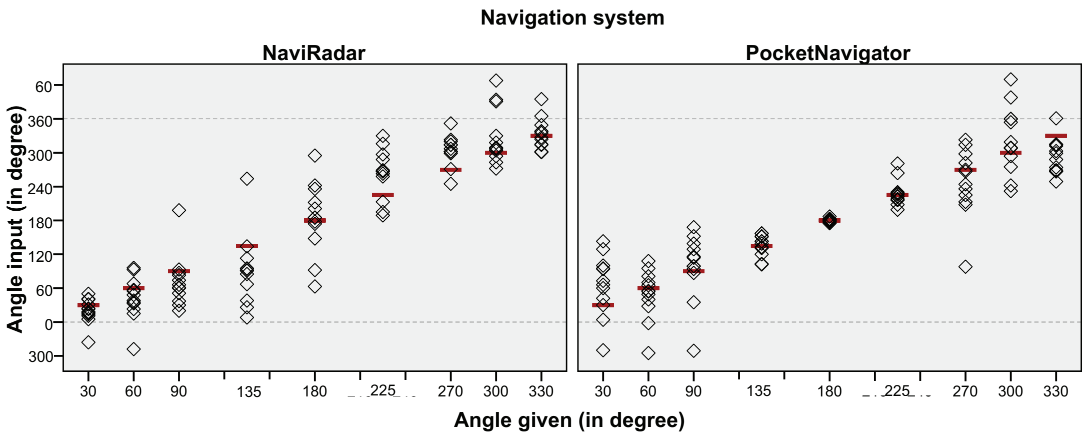


Figure 6.20 – Input distribution for each angle, red lines show the correct angle

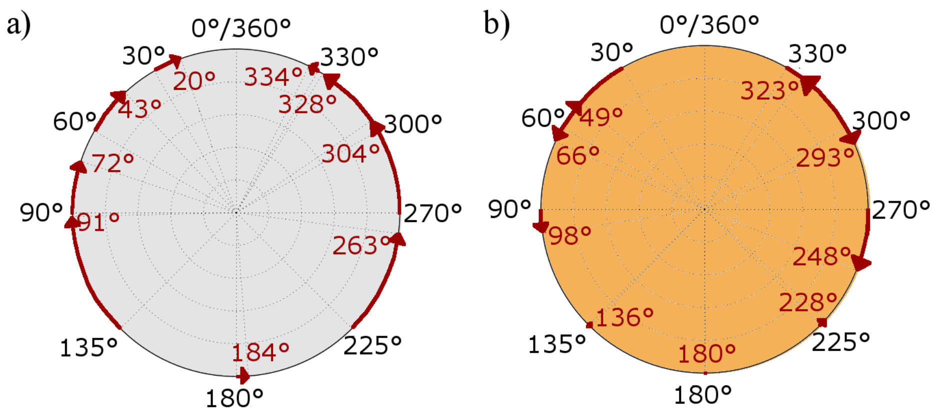


Figure 6.21 – Mean input values for each angle for a) NaviRadar and b) PocketNavigator

directions of 30° and 60° in each direction fall into one feedback interval, one would think that the results for these given angles are about the same. However, as the arrows in Figure 6.21 show, inputted directions for 60° are with 49° on average closer to 0° than for 30°, where the average input was 66°, even if participants were presented the same signal. No conspicuous pattern in the randomised order of presented angles could be detected.
Pearson correlation coefficients ($N = 216$, $p < 0.001$) shown in Table 6.2 were computed to assess the relationship between the direction that was presented (angle given) and recognised (angle

input). For both systems, a strong positive correlation could be found, meaning that it is possible to recognise a presented direction.

	NaviRadar	PocketNavigator
r	0.93	0.90

Table 6.2 – Correlation coefficients for relationship between presented and recognised direction

Deviation from communicated angle Figure 6.22 shows the mean deviations of inputs from the presented directions. A higher bar means that the input differed more from what was presented. The results for the two examined systems show that contrary deviations were achieved depending on the angle. Both systems provide similar deviations for the most common type of crossing, a

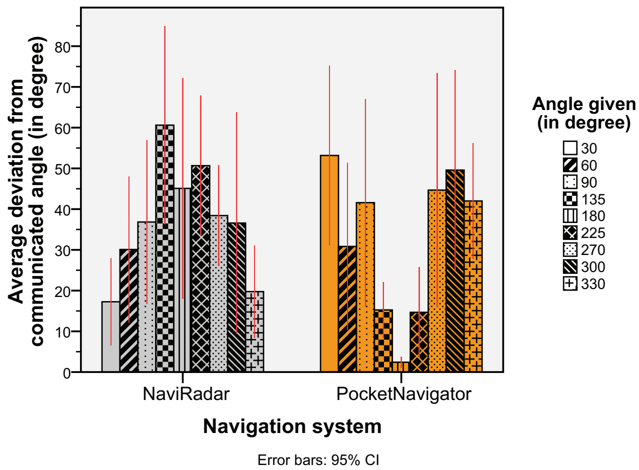


Figure 6.22 – Average deviation from communicated angle for NaviRadar and PocketNavigator per angle

90° turn to the left and right, with slightly better results of 36.83° and 38.42° for left and right with NaviRadar than 41.58° and 44.67° with the PocketNavigator. Apart from that, it is easier to recognise small angles with the NaviRadar concept, while for the PocketNavigator it seems to be easier to determine angles that lie in the back area of a person. Referring to user comments during the study, small angles in NaviRadar are easier to determine because the two vibrations are presented close one after another and hence it is not that important to concentrate on the timing. On the other hand, large angles and especially the 180° vibration pattern presented by the PocketNavigator are most distinct, which makes it easy to recognise them.
As already discussed in Chapter 5.8, it might be more important for a navigation task to provide distinct directions in the front area, because directions in the back turn to front directions as soon as you turn towards them, so NaviRadar might be advantaged in this regards.
The study design might have influenced these results. As the tested angles 90°, 135°, 180°, 225° and 270° refer to the directions lying in the middle of the intervals presentable by PocketNavigator, and no directions at the edges of those were tested, the drawback of low resolution could not be shown.

Input time Figure 6.23 shows the average input times during the training phase. The reason the input time for the PocketNavigator ($M = 3.9$ seconds, $SD = 0.4$) is shorter than for NaviRadar ($M = 5.0$ seconds, $SD = 0.3$) may be due to the timing of feedback, that is given once every three seconds (duration of one rotation) for NaviRadar, while it is repeated every 1.5 seconds for the PocketNavigator, as the scanning mode was used for training. In other words, participants listened to the respective vibration pattern on average 1.7 times when training NaviRadar, while 2.6 times for the PocketNavigator. This would indicate a faster reaction to the direction presented by NaviRadar, however, the average time of 3.9 seconds for PocketNavigator is also short and might be the minimum time needed for inputting the direction.

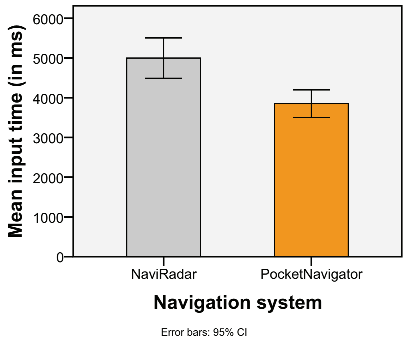


Figure 6.23 – Input time per system

6.8 Conclusion

The low number of overall errors shows that all three tested systems performed well in a realistic navigation task, with the same low error count for all three systems, and a low number of disorientation events for AudioGuide and NaviRadar. It could be observed that when no GPS problems occurred, participants using NaviRadar could walk as fast as with the AudioGuide, both system indicate the next direction in advance. Furthermore, the tactile interfaces were said to be useful to indicate an overall direction, for hiking or when it is less important to find the shortest way [72].
However, some participants mentioned explicitly that they would always prefer a map over all three systems, because they want to have an overview of the area they are walking in. But some of them had not used turn-by-turn guidance before, and one participant said during the first test it would be nice to have some kind of visual feedback, but changed his mind after the third run and said he now prefers to not need to look at the screen and rely on audio and/or vibrations only. He even mentioned the advantage of nonvisual feedback, to be able to concentrate on the surrounding. Overall, participants often looked onto the screen, even if there was nothing to see but a black screen, indicating that they are used to always get some visual feedback.
The AudioGuide achieved overall best results, referring to comments mainly because it is familiar and easy to understand without learning and thinking. This suggests that more training with tactile interfaces, to get similarly used to them, could strongly improve the results of other systems. Moreover, there are several drawbacks of auditory instructions. In a noisy environment it can be difficult to perceive instructions, while in a quiet setting, it can be annoying if others can also hear them. Headphones can solve both problems, but they cut off the user from the environment and make it harder to perceive important sounds like from approaching cars, and are inappropriate when walking in a group of several people. The applicability can be restricted by language and measurement unit, moreover, the judging of distances of instructions such as *"In 45 metres, turn left"* seemed to cause mental demand and errors, when users thought they needed to turn earlier than they actually had to. If an instruction is missed, it is difficult to repeat it in most existing audio systems. In contrast, the constant feedback of the other two systems does not interrupt other tasks but one can listen to them when enough attention is available, or even feel intuitively where to go without shifting the attention actively towards the feedback.

For all participants, vibrational feedback for navigating was new, but said to be very interesting and promising. Moreover, after completing the study, it had become conceivable to use it. While 75% said they can imagine using the AudioGuide, still 50% would like to try NaviRadar or PocketNavigator, if it was available to use.

6.9 Ideas

Several ideas how to improve the feedback of NaviRadar have come up during the user study.

Special indications Special indications can be used for specific events, however, they have to be learned and mean an interference with the so far consistent feedback. However, there are several exceptional situations where an obtrusive signal might be appropriate.

1. When the destination is reached. This can be implicitly indicated by stopping the feedback, or by giving a special signal like three long pulses (800-200-800-200-800) [71] before stopping
2. When a turn has been successfully completed. Some participants said the concept is missing a confirmation signal. So far this is given implicitly by no longer showing the direction to turn, as the indication of direction stops as soon as the user has turned towards the correct direction at a crossing, because then the current and desired direction coincide. This is similar to the concept of the PocketNavigator, were the feedback changes for instance from *long-short* to *short-short* after a successful turn, which is also not an explicit signal, but was regarded as such. A possible solution could be to present a longer heartbeat after a successful turn.
3. When two directions close to each other are available. Therefore, the accuracy of the system might not be enough, and the system should warn the user that possible ambiguous signals are available and to take extra care with this turning decision. A possible way would be to present a signal with more than two pulses, where the excess of vibrations stands for multiple possible ways.
4. When a navigation error has occurred. This is the event where a special indication is most urgent. Figure 6.24 shows a situation, where the user was supposed to go straight at x_{n-1} but took a left turn. Now he could be presented to go right, where the current next route point lies, but this indication could also be understood as an advance notice of the next upcoming crossing. In this case it is needed to inform the user obtrusively so that he turns around and can be guided back towards the correct next route point. A possible way to communicate this could be a signal like the insistent one used by Chan [14] containing two long pulses with a short break in-between (700-100-700) instead of the normal short heartbeat.

Audio output Audio output could be offered as an additional or alternative output mode by replacing vibrations with audio beeps. One participant, who was with 46 years older than the average, mentioned that he had problems to feel the vibrations produced by the mobile phone (not with the C2 tactor) and that it would be useful to support the perception by adding audio output.

Show different directions Pielot et al. [67] who developed a tactile belt, presented different directions to compensate the disadvantage of tactile interfaces in comparison with auditory instructions, where the next turning instructions is given in advance (*"In 20 metres, turn left, and then after 45 metres, turn right"*). Alternately, directions of the next and following waypoint were

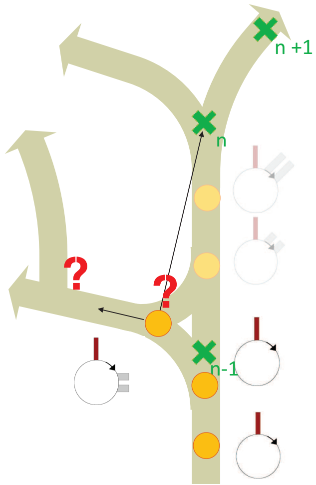


Figure 6.24 – Situation, where an navigation error has occurred, but a simple indication of the correct direction does not work

presented with distinct vibrations. Alternatively, the overall direction to the destination could be shown to allow the user to look for shortcuts, or use his knowledge about the area to look for ways. However, it needs to be taken care of not to make the interface too complex as that would make it less intuitive and harder to use.

Special gesture Another idea to improve the interface is to allow the user to stop or at least quiet feedback when an instruction is understood, as otherwise it could become annoying to get more and stronger vibrations when the user already knows where to go. This could be realised in form of a gesture with the mobile phone, or a specific button or touchscreen gesture, such as swiping from left to right or vice versa to acknowledge the instruction has been understood.

7 Conclusion

In this thesis, the design, implementation and evaluation of NaviRadar, a novel interface using vibrations to convey navigation information for pedestrians has been described. As an alternative to visual or auditory interfaces, tactile feedback allows a hands-free usage without the restrictions of auditory feedback in noisy or too quiet environments, or when walking together with others. Turning instructions coded as distinct vibrations using a radar metaphor proved to be easy to understand, while arbitrary directions could be presented.

7.1 User studies

A first study investigated if the idea is understandable and realisable. Moreover, several different patterns to create distinct vibrations for the two presented directions current and desired, have been evaluated, as well as distinct vibrations to show the distance to the next turn. The results show that using simple rhythms containing either one or two pulses, should be used to distinguish between the directions, while intensity turned out to be a suitable parameter to indicate the distance, where a weak pulse stands for a far, an intense for a close turn. Moreover, the first study showed that the overall idea of the imaginary rotating radar works, at least in a controlled environment. Furthermore, a training effect from run 1 to 6 of more than 30% in terms of the accuracy a direction can be recognised shows that the performance using in most cases unfamiliar tactile feedback can be increased successfully in a short time. A second study was conducted to follow up these findings and to show the applicability of NaviRadar in a realistic outdoor navigation task. Compared to another system using tactile feedback, it turned out to be important to provide instructions in advance to allow users to adjust oneself to change the directions soon. In comparison with a system giving tactile notifications and speech instructions, the mental demand and effort participants had to make to use the systems was higher when using NaviRadar, mainly because vibrational feedback is unfamiliar for most users. However, in terms of frustration and usability, no difference in the ratings could be detected indicating that NaviRadar can be a useful feature for navigation systems allow an unobtrusive turn-by-turn guidance.

7.2 Challenges

In the beginning, the performance of the internal compass of the Motorola Milestone used for this thesis was thought to be worse than it was in the end. A lot of effort has been put into comparing it to an external one including a tilt-compensating compass chip, to provide the best possible hardware for the tests of the new tactile interface concept. The results surprisingly did not show big differences, indicating that the internal compass could have been used for the outdoor study. However, as vibrations were created using an external vibrator to allow a wider range of feedback, it turned out to be useful to have a full functional compass attachable via bluetooth.

For the outdoor study, it would have been beneficial in terms of internal validity to avoid additional *variance* between systems, and use the same compass for all systems. However, for NaviRadar, the C2 tactor was used to allow short intense pulses, and different intensities and therefore it was not possible to use the internal compass for this system, as it was done for the PocketNavigator. This system, in turn, could not use the external compass as it was mounted to the distance holder and meant to be held straight, which would have taken away a feature of PocketNavigator, not having to hold the phone flat in the hands. Preceding compass test at least showed that performances of the two used compasses are similar and influences on the results are unlikely. A problem during the testing outside were the variable accuracy of GPS measurements. This caused positioning problems in the outdoor study, resulting for instance in instructions not to be given at the correct location, so the researcher had to intervene. This is a general problem for navigation systems, especially when high accuracies are needed like in the domain of pedestrian positioning, but with

further improvements for GPS regarding multipath or the launch of Galileo in the next years, these problems could be solved.
With the benefit of hindsight, the design of the outdoor study had a drawback regarding the comparison between NaviRadar and PocketNavigator. The design of the training application, where the data for the analysis was collected, was taken from the first study, where different patterns for NaviRadar had been compared. The tested angles were distributed over the whole circle, however, they all lay in the middle of the feedback intervals used by the PocketNavigator. To reveal the drawback, that only these values can be shown with high accuracy, while angles at the edges of the intervals will lead to deviations, the test angles would have needed to be distributed arbitrarily over the whole circle. Therefore, the results for PocketNavigator are positively biased regarding the mean deviation from the presented angle.

7.3 Conference paper

The work and results from this thesis have been outlined in a conference paper (see Appendix C) submitted to the ACM CHI Conference on Human Factors in Computing Systems [134] in the category "Interaction Using Specific Capabilities or Modalities", which will take place in May 2011. Its title is "NaviRadar: A Novel Tactile Information Display for Pedestrian Navigation".

7.4 Future work

The concept of NaviRadar has proven to work in two user studies, but still more testing has to be performed, with a focus on unobtrusiveness and intuitive understanding. One area for further work lies in the investigation of different rotation speeds. It would be interesting to see if accuracy increases with a slower or faster rotation, and at which point vibrations come too fast to understand the signals, or the feedback becomes annoying. Moreover, it can be investigated if the direction of the rotation has an influence on the results, and if for example the worst recognised angle is no longer 135°, but 225°, the mirrored direction on the other side. Interesting extensions of the concept have been discussed in Chapter 6.9. One feature for the tactile interface could be to allow users to choose between auditory and tactile feedback in different situations, while the radar concept remains the same. In this way, situations can be investigated where audio is advantageous, and if people are willing to use headphones for a navigation task, and where and when they prefer to be guided by the tactile interface.
After the first study, the practical application of NaviRadar has been discussed where the potential of the dynamic scanning of directions has been highlighted. However, this has not been investigated in the second study, where the focus lay on the general usability of the tactile commands while walking. Further studies should investigate this aspect of the system as it is critical in regards of navigation errors and therefore user satisfaction.
A further step in the development is to extend the current prototype to be fully functional and allow NaviRadar to be tested by a wider audience to get more qualitative and quantitative feedback about the interface concept. Furthermore, prolonged usage of NaviRadar can give insights in the effect of training on the performance of tactile interfaces. Therefore, maps and routing data can be taken from the OpenStreetMap project [120], where already a lot of specific pedestrian ways are included. However, routing databases for pedestrian navigation still have to be extended to include more pedestrian-only ways, and with a higher accuracy, to avoid navigation errors or detours and therefore allow users to trust the instructions given.
This work can also be a basis for tactile interfaces in other domains. Rhythm and duration showed to be suitable parameters, while roughness was perceived with individually varying precision. Providing a metaphor for abstract vibrations is useful and can be supported by finding an equivalent presentation in another modality, like participants in the user studies were first taught the operating mode with the help of a visual radar, before relying on the tactile feedback only.

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Contents of the CD

/Conference ....submitted paper and video

/Presentation ....slides and video

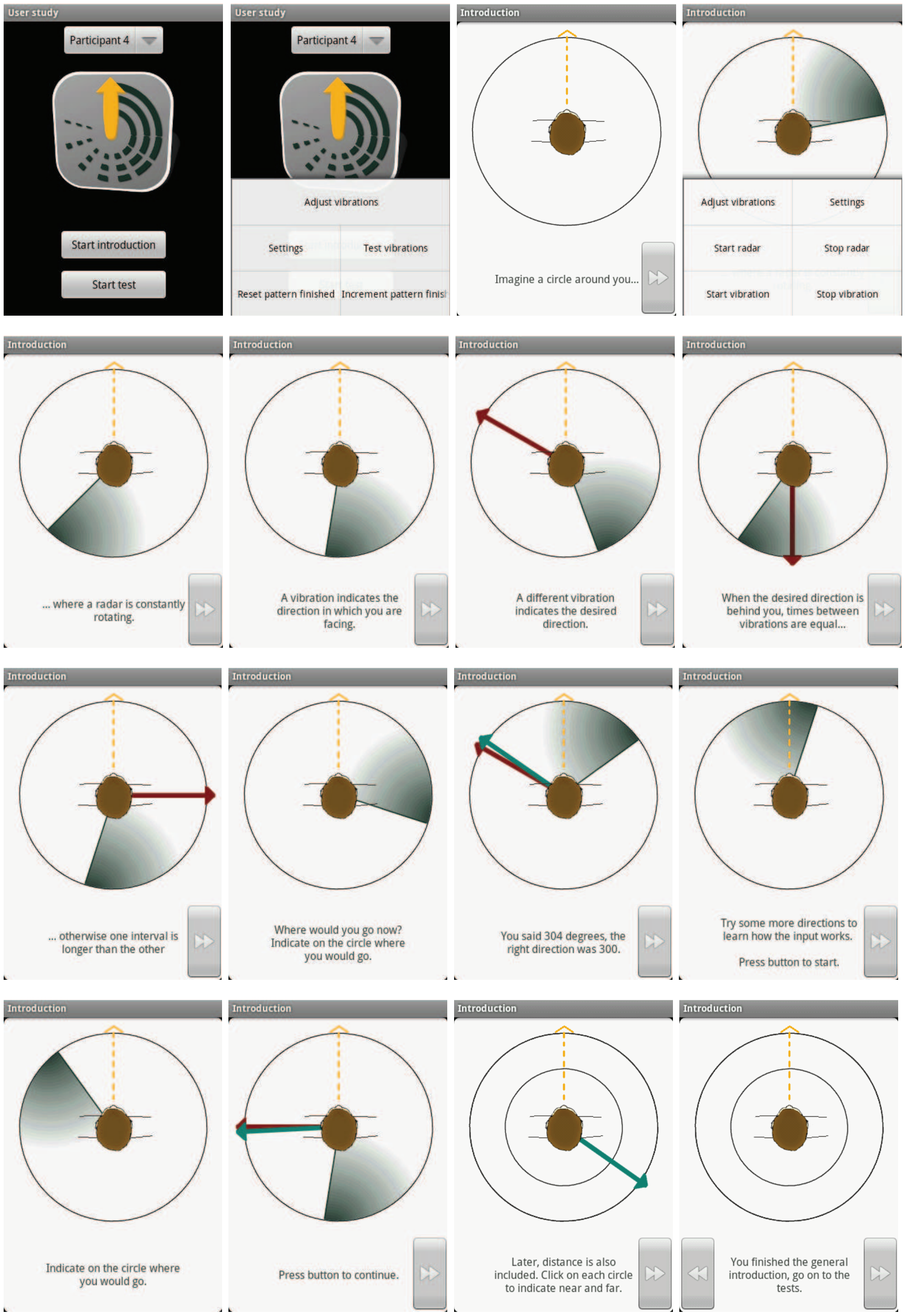
/Thesis ....electronical version and LaTeX files

- /Bib
  - /References
  - /Web-References
- /Data
- /Images

/User Studies

- /Analysis ....statistical analysis
  - /Excel
    - /Indoor study
    - /Outdoor study
  - /Matplotlib
    - /Indoor study
    - /Outdoor study
  - /SPSS
    - /Indoor study
    - /Outdoor study
- /Design ....experimental design
  - /Indoor study
  - /Outdoor study
- /Logs ....log files
  - /Indoor study
  - /Outdoor study
    - /Training performances
    - /GPS traces
- /Observations ....observations and comments
  - /Indoor study
  - /Outdoor study
- /Prototypes ....Android projects, apk-files and screenshots
  - /Indoor study
  - /Outdoor study
    - /Training application
    - /Naviation application
  - /Performance data

8 APPENDIX A: Study Material - The ideal vibrational pattern



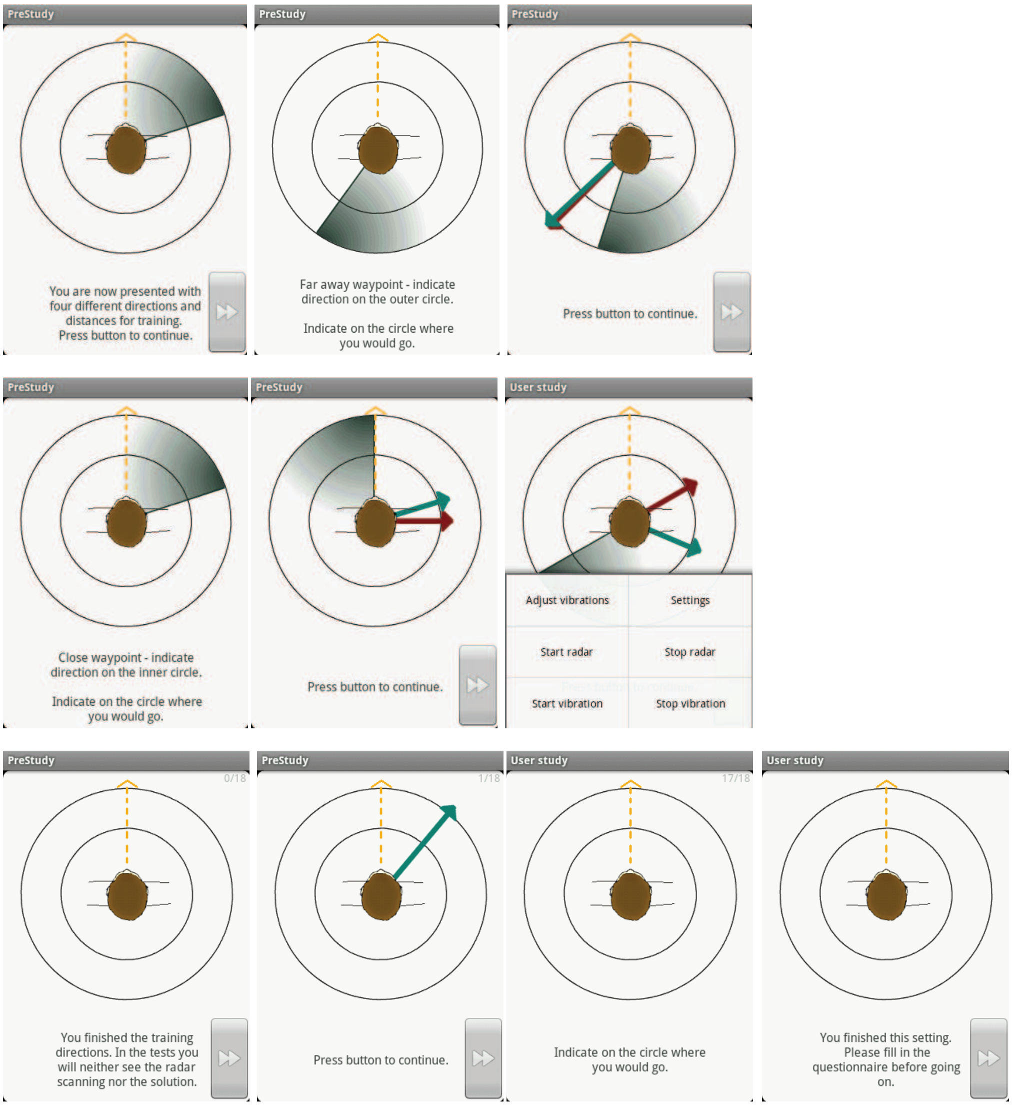
Screenshots test application (1/3):

First row: Start. Start (menu). Introduction (1) (without radar). Introduction (menu).
Second row: Introduction (2-5)
Third row: Introduction (6-9)
Forth row: Introduction (10-11), repeated 4 times. Introduction (12-13)

Screenshots test application (2/3):

Descriptions and introduction screens for all six patterns:

$P_{DU,IN}$, $P_{DU,RH}$, $P_{DU,RO}$, $P_{IN,IN}$, $P_{RH,IN}$, $P_{MO,IN}$



Screenshots test application (3/3):
First row: Training (1). Training (2-3) (distance=far), repeated 2 times.
Second row: Training (4-5) (distance=close), repeated 2 times. Training (menu).
Third row: Test (1). Test (2-3), repeated 18 times. Test(4).

QUESTIONNAIRE

ParticipantID _____

GENDER O male O female

AGE _________

PROFESSION ____

YOU NORMALLY HOLD YOUR MOBILE IN YOUR O left hand O right hand

HOW WOULD YOU DEFINE YOUR EXPERIENCE WITH

	None	Poor	Medium	High	Expert
… COMPUTERS?	1	2	3	4	5
… MOBILE PHONES?	1	2	3	4	5
… CAR NAVIGATION?	1	2	3	4	5
… PEDESTRIAN NAVIGATION?	1	2	3	4	5

HAVE YOU ANY EXPERIENCE WITH VIBRATIONAL FEEDBACK LIKE

O Vibration alarm e.g. when phone in silent mode

O Game controller

O Vibrations as touchscreen feedback

O Others, namely

____

____

Pre-Questionnaire

*TaskID*______ *ParticipantID* _____

	Strongly disagree	Disagree	No opinion	Agree	Strongly agree
This representation of **direction** was clear and understandable	1	2	3	4	5
This representation of **direction** was intuitive	1	2	3	4	5
This representation of **distance** was clear and understandable	1	2	3	4	5
This representation of **distance** was intuitive	1	2	3	4	5

	Very high	High	Moderate	Low	Very low
The mental effort to understand the vibrations in this setting was	1	2	3	4	5

How would you rate this setting on a scale from

Very bad	1	2	3	4	5	6	7	Very good

Could you think of metaphors to easily remember the meanings of the different vibrations?

O no O yes, namely ____

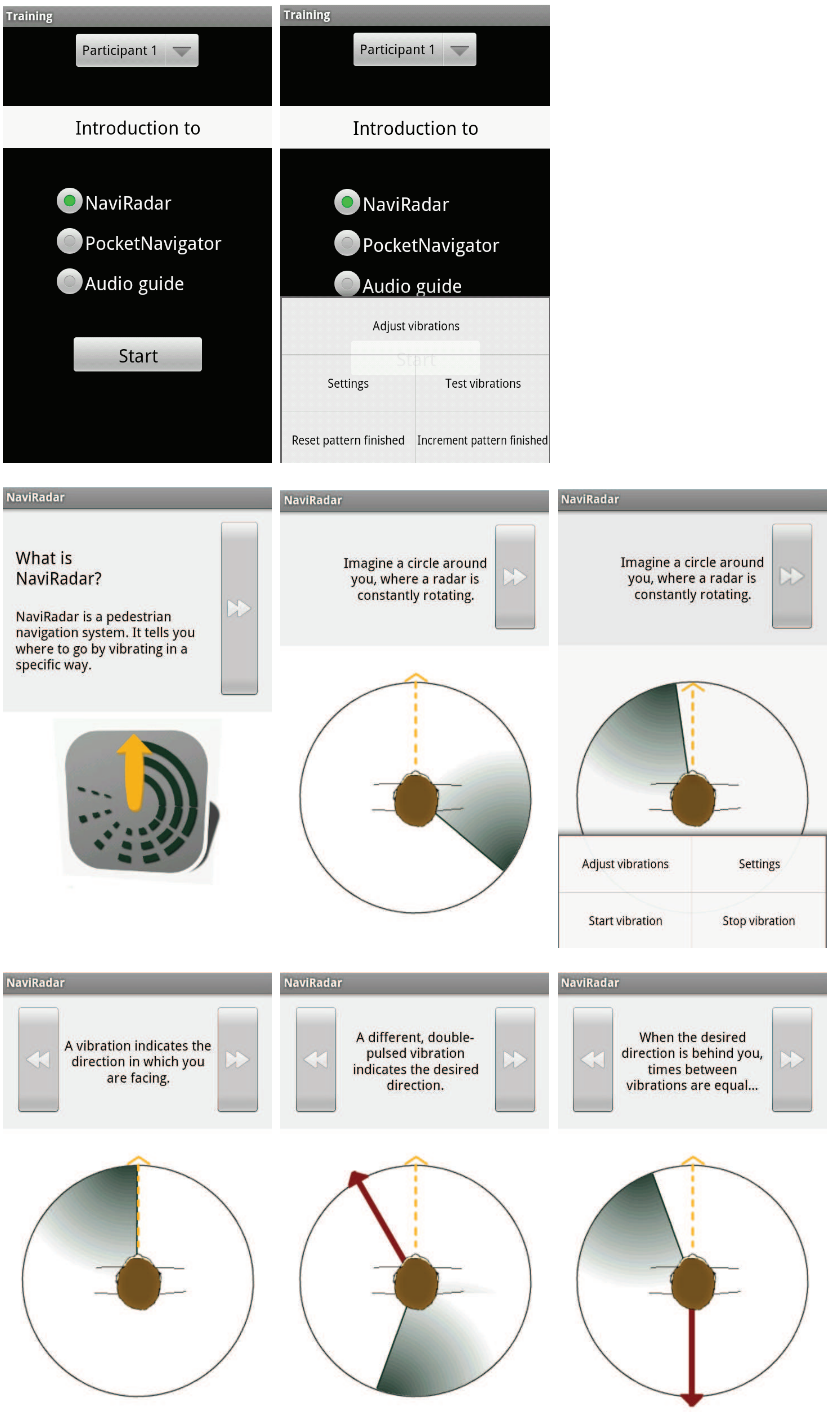
Comments:

____

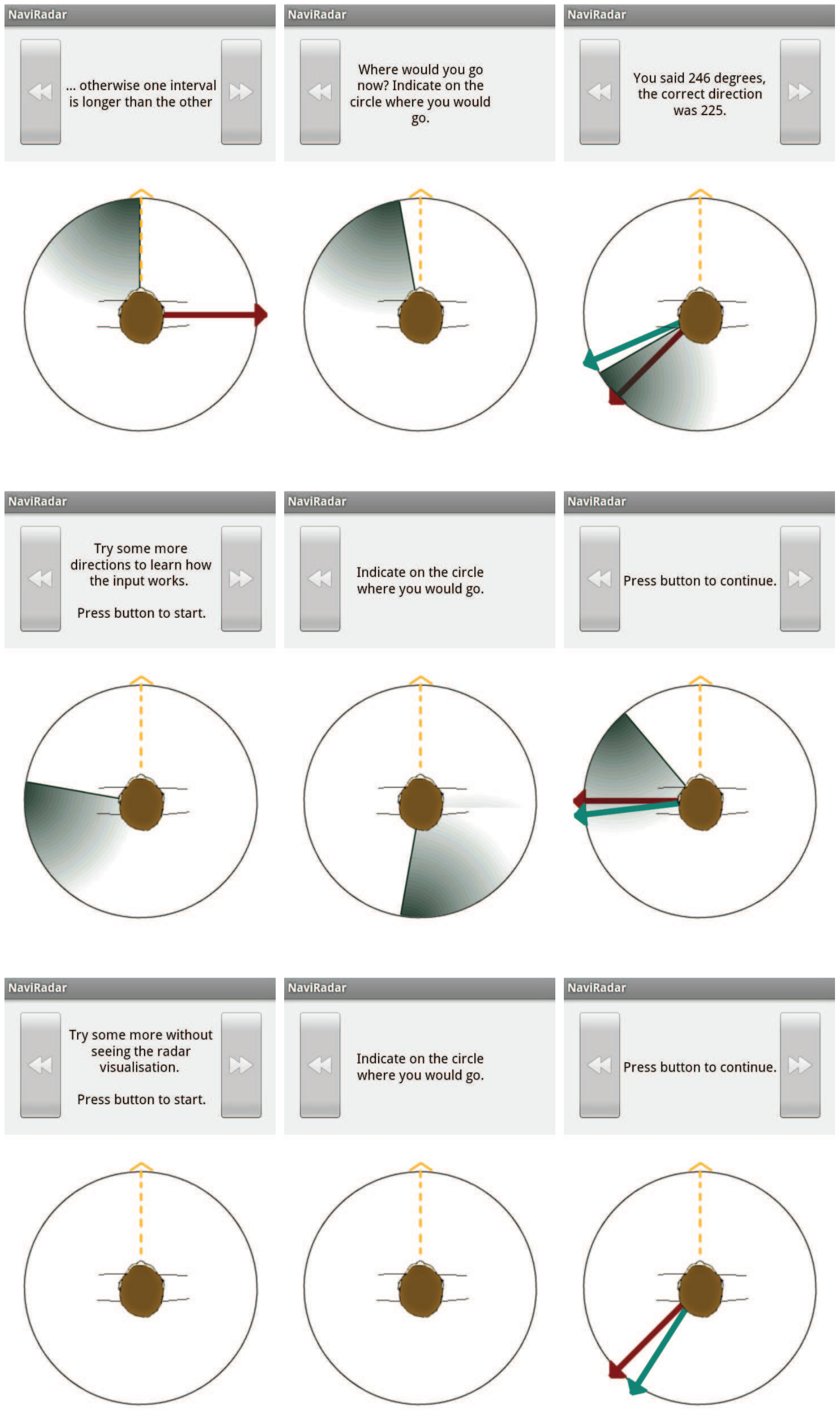
____

After-Pattern-Questionnaire

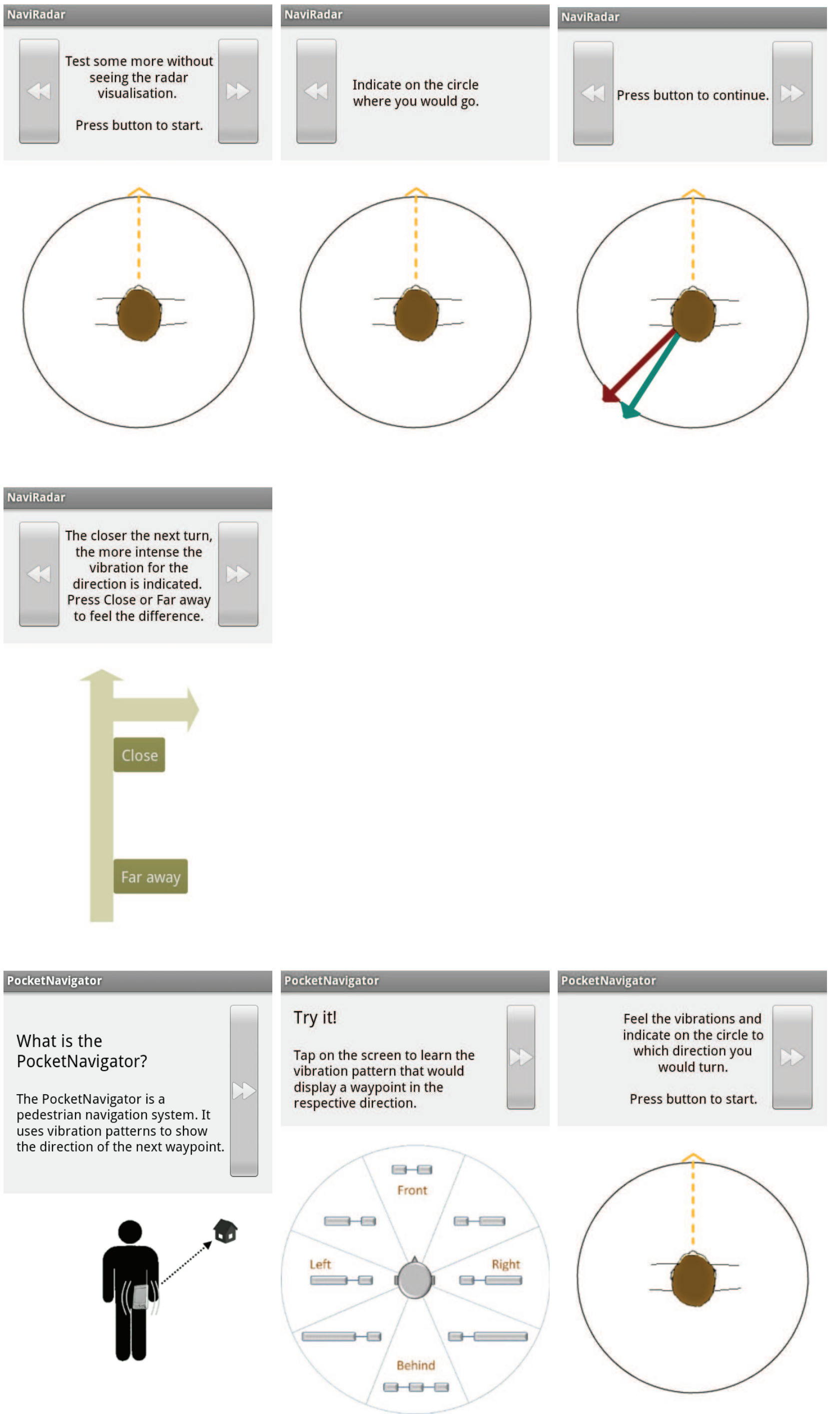
9 APPENDIX B: Study Material - Testing in a realistic setting



Screenshots training application (1/4):
First row: Start. Start (menu).
Second row: NaviRadar (1-2). NaviRadar (menu).
Third row: NaviRadar (3-5).



Screenshots training application (2/4):
First row: NaviRadar (6). NaviRadar training (7-8).
Second row: NaviRadar (9). NaviRadar training (10-11), repeated 4 times.
Third row: NaviRadar (12). NaviRadar training (13-14), repeated 4 times.

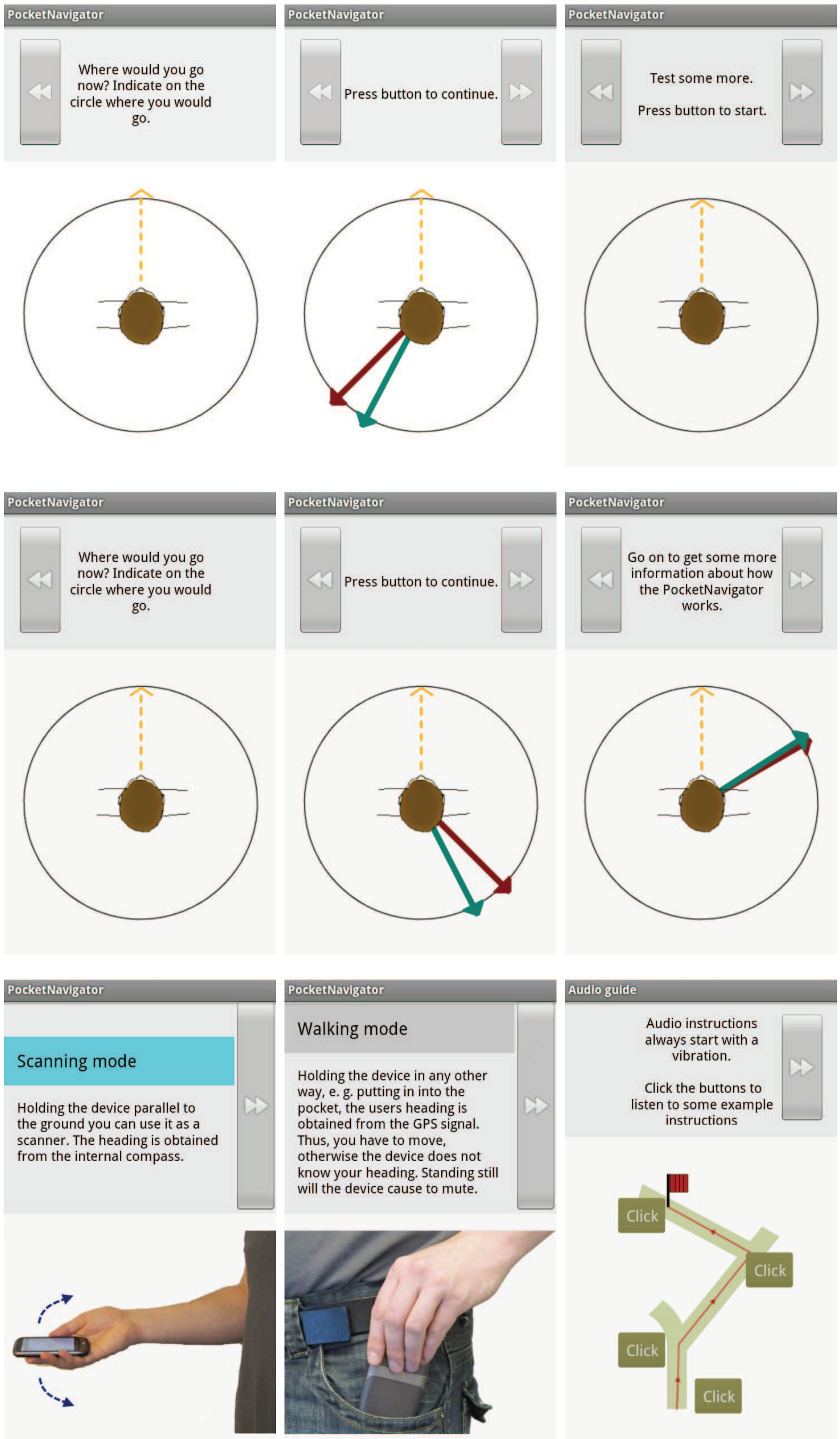


Screenshots training application (3/4):

First row: NaviRadar (15). NaviRadar test (16-17), repeated 9 times.

Second row: NaviRadar (18).

Third row: PocketNavigator (1-3).



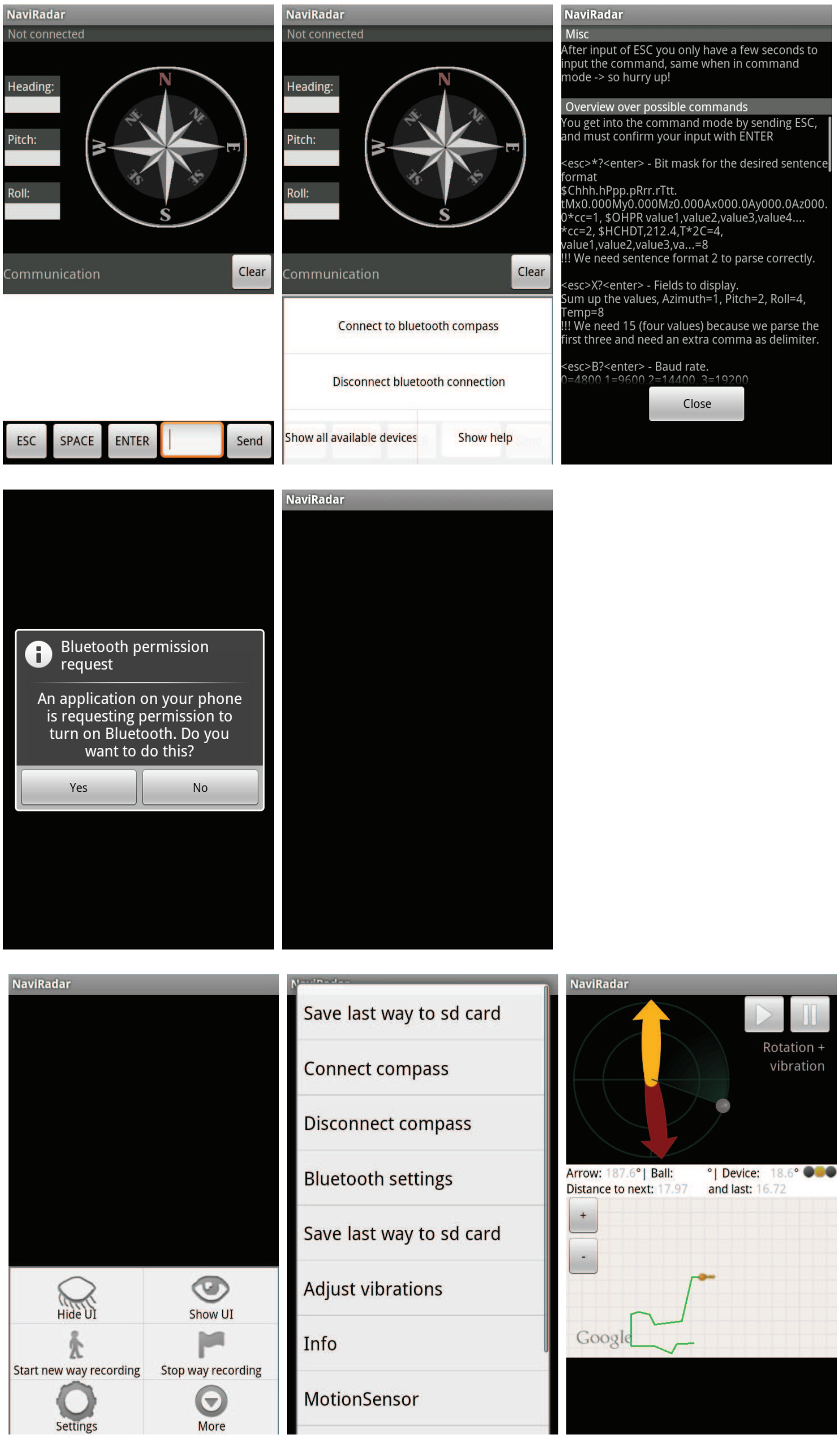
Screenshots training application (4/4):
First row: PocketNavigator training (4-5), repeated 9 times. PocketNavigator (6).
Second row: PocketNavigator test (7-8), repeated 9 times. PocketNavigator (9)
Third row: PocketNavigator (10-11). AudioGuide.

Screenshots test application (1/2):

First row: Start. Start (menu).

Second row: WayViewer. WayViewer (menu).

Third row: Importer. Start → Settings (1-2).



Screenshots test application (2/2):

First row: Compass activity. Compass activity (menu). Compass activity → Help

Second row: Bluetooth reminder. Navigation activity (black screen during study).

Third row: Navigation activity (menu 1-2). Navigation activity (debug screen).

```
<?xml version="1.0" encoding="ISO-8859-1" ?>
<xs:schema xmlns:xs="http://www.w3.org/2001/XMLSchema">
  <xs:element name="way">
    <xs:complexType>
      <xs:element name="waypoints" minOccurs="0" maxOccurs="1">
      <xs:complexType>
        <xs:element name="waypoint" minOccurs="0" maxOccurs="unbounded">
          <xs:complexType>
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            <xs:element name="longitude" type="xs:integer"/>
            <xs:element name="dist_last" type="xs:decimal"/>
            <xs:element name="dist_next" type="xs:decimal"/>
            <xs:attribute name="id" type="xs:positiveInteger"/>
            <xs:attribute name="way_id" type="xs:positiveInteger"/>
            <xs:attribute name="timestamp" type="xs:positiveInteger"/>
          </xs:complexType>
        </xs:element>
      </xs:complexType>
      </xs:element>
      <xs:attribute name="id" type="xs:positiveInteger"/>
      <xs:attribute name="route_id" type="xs:positiveInteger"/>
      <xs:attribute name="participant_id" type="xs:positiveInteger"/>
      <xs:attribute name="system_id" type="xs:positiveInteger"/>
      <xs:attribute name="start_time" type="xs:positiveInteger"/>
      <xs:attribute name="end_time" type="xs:positiveInteger"/>
      <xs:attribute name="comment" type="xs:string"/>
    </xs:complexType>
  </xs:element>
</xs:schema>
```

way.xsd: XML schema for logging of positioning data

System ______

Route ______

ParticipantID ______

	Strongly agree	Agree	Neither agree nor disagree	Disagree	Strongly disagree
1. It was **simple to use** this system.	1	2	3	4	5
2. I was able to **complete the navigation tasks quickly** using this system.	1	2	3	4	5
3. I felt **comfortable** using this system.	1	2	3	4	5
4. It was **easy to learn** to use this system.	1	2	3	4	5
5. The information provided by the system was **easy to understand**.	1	2	3	4	5
6. I felt **confident** with the feedback provided by this system.	1	2	3	4	5
7. I **liked** using the interface of this system.	1	2	3	4	5
8. I believe I could **become productive quickly** using this system.	1	2	3	4	5
9. Overall, I am **satisfied** with this system.	1	2	3	4	5

	Very low	Low	Undecided	High	Very High
A. Mental demand. How much mental and perceptual activity was required (e.g. thinking, deciding, calculating, remembering, looking, searching, etc.)? Was the task easy or demanding, simple or complex, exacting or forgiving?	1	2	3	4	5
B. Effort. How hard did you have to work (mentally and physically) to accomplish your level of performance?	1	2	3	4	5
C. Frustration level. How insecure, discouraged, irritated, stressed or annoyed did you feel during the task? (vs secure, gratified, content, relaxed, and complacent)	1	2	3	4	5

How would you rate your overall walking speed using this system?	**Very slow**	**Slow**	**Normal**	**Fast**	**Very fast**

Positive Aspect: ______________________________

Negative Aspect: ______________________________

Would you use this system outside the study? yes no

Ideas for improvements/further features/comments

____

____

After-Pattern-Questionnaire

QUESTIONNAIRE

ParticipantID _____

Gender	male	female
Age	________	
Profession	________________________________	
You are	left hand	right hand

How would you define your experience with

	None	Poor	Medium	High	Expert
… computers*?*	1	2	3	4	5
… mobile phones?	1	2	3	4	5
… car navigation/Sat navs?	1	2	3	4	5
… pedestrian navigation (paper maps)?	1	2	3	4	5
… pedestrian navigation (electronic devices)?	1	2	3	4	5

Have you any experience with vibrational feedback like

O Vibration alarm e.g. when phone in silent mode

O Game controller

O Vibrations as touchscreen feedback

O Others, ________________________________

How familiar was the Alexandra Park for you before you participated in this study:

O never been there

O been there a few times

O know it very well

Post-Questionnaire (1/2)

Did you ever have an accident while walking because you were concentrating on the phone screen?

Do you have any concerns about displaying your phone in the public (e.g. having it stolen, embarrassed)?

When you are using a navigation system (e.g. map,tourist guide, electronic device) while walking, does it bother you when other people notice it? Why?

Please state your first, second, and third preference.

Navigation system	Preference	Why?
NaviRadar		
PocketNavigator		
Audio + Vibrations		

Something you liked from the study?

Something you disliked from the study?

Any further comments or suggestions?

Post-Questionnaire (2/2)

NaviRadar: A Novel Tactile Information Display for Pedestrian Navigation

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 six different tactile patterns to communicate the two different directions. 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, the user is able to concentrate on the main task of walking as visual attention is not required. Moreover, the lack of audio attention enables it to be used in noisy environments.

Author Keywords

Pedestrian navigation, tactile feedback, radar.

ACM Classification Keywords

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.*

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 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 novel 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.

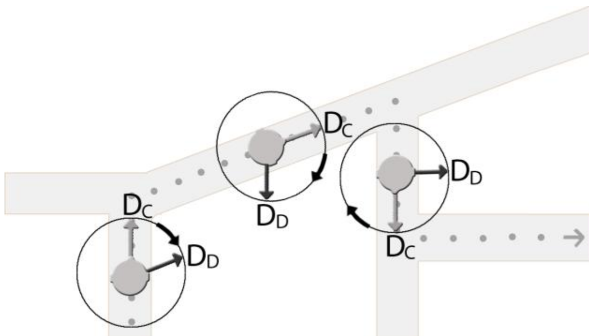


Figure 1. NaviRadar concept illustrating a path where the user has to turn right, right again and left (D_C – current direction, D_D – desired direction)

The user is able to differentiate between the two directions as they are communicated via different tactile patterns called tactons [1]. 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 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 (e.g. Ovi Maps). 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 (e.g. “turn right in 50 meters”), text (e.g. current street or destination), 2D route sketches (e.g. an arrow pointing in the correct direction), routes on 2D or 3D maps, and combinations of the previously mentioned possibilities [2]. 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 [3,4]. 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 [5]. 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 [6].

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. Such intrusion may occur when walking with friends or colleagues; maybe with other pedestrians. Furthermore, spoken instructions may not be received in noisy environments, such as a busy crossing or during a conversion [7]. This could be improved by wearing headphones as they could provide louder audio feedback and help block environmental noise. On the other hand, the ability to hear one’s environment can be very important – hearing an approaching car, for example.

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 such a lamp posts) as much as visual and auditory information do. A further advantage of the communication of navigation information via tactile (and also auditory) feedback is that it can be felt or heard by visually impaired people. A range of different parameters, such as frequency, amplitude (intensity), duration, timing and rhythm, can be changed in order to create different tactile patterns [8]. With multiple vibrators [1], further parameters, such as location of vibration [5], movements [9] or speed [7], could be manipulated.

Tactile feedback can be used as a reminder for the user to view the screen or to listen to spoken instructions. A popular usage of Ovi Maps is to simply hold the mobile phone in one’s hand while walking. Before spoken instructions are provided, the mobile phone vibrates shortly. This gives the user sufficient time to bring the phone to their ear in order to hear the instructions more clearly. Once listened to, the user can then move the phone back into a more comfortable position.

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 [5], thumb and forefinger [10] or left and right shoulder [11]. Other prototypes involved several vibrators attached to a belt [12] or vest [13] 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 [14].

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* [15]. 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) [16]. 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.

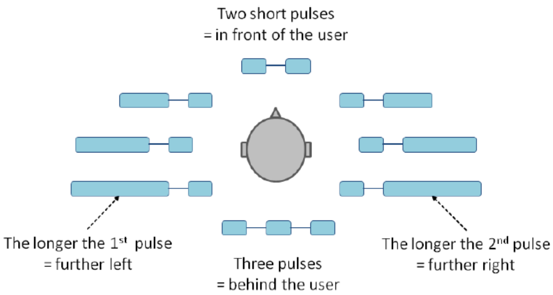


Figure 2. PocketNavigator tactons to communicate direction [16]

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 [17]. The system does not provide turn-by-turn instructions, though it does help the user to travel in the correct direction. This interaction technique is not appropriate for many situations as the system does not help the user to find a short path to the destination. 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 [18] provides navigation instructions via the combined use of a public display and a mobile device. The Rotating Compass is 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. A corresponding field study showed the feasibility, usability, and performance of this interaction technique. 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, roughness and location of the vibration are good candidates and should be tested in our study.

Table 1 shows the six 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.

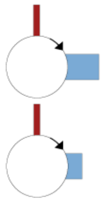
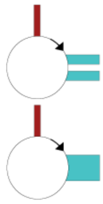
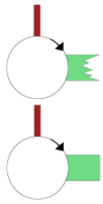
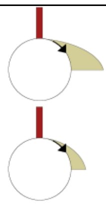
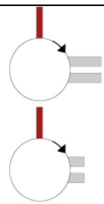
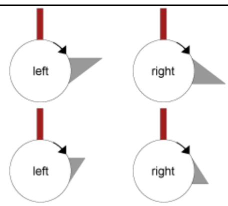
		Distance		
		Intensity	Rhythm	Roughness
Direction	Duration	 DurInt	 DurRhy	 DurRou
	Intensity	 IntInt		
	Rhythm	 RhyInt		
	Motion	 MotInt		

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

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.The forth row shows *MotInt* which uses two different vibrators in order to communicate motion (a transition in vibration strength from left to right or right to left). The icons in the table show a motion from left to right (as the user has to go to the right hand side) by decreasing the intensity of the left vibrator while increasing the intensity of the right vibrator.

When using intensity, rhythm and motion 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 - anonymized for blind review -* , 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 or two EAI C2 tactors [19] were 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 [20,7]. 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 tactors on the phone and where fingers are placed on them during the study. The C2 actuators were 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 one or two C2 tactors.

Experimental Design

The experiment used a within-subjects design with three independent variables: **tactile pattern** containing the six levels from Table 1 *(DurInt*, *DurRhy*, *DurRou*, *IntInt*, *RhyInt* and *MotInt)*, **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 an explanation of the overall aim of the study. This was followed by 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.

Figure 4. Study setting and participant interaction position

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.

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.

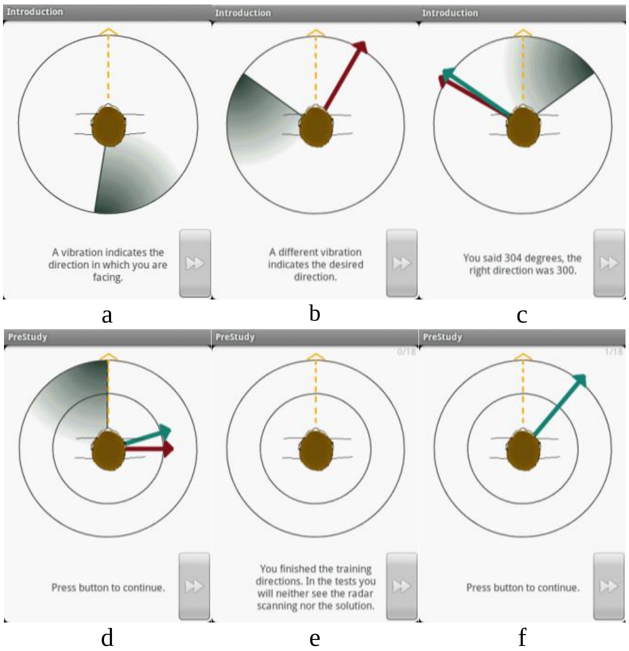


Figure 5. Test application running on a laptop.

Following the training stage, the participants were asked to wear headphones playing a mixture of white noise and typical street noise [21]. These were used to block any sounds generated by the C2 tactors. Then, they were presented with one of the six 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.

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 24° 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.

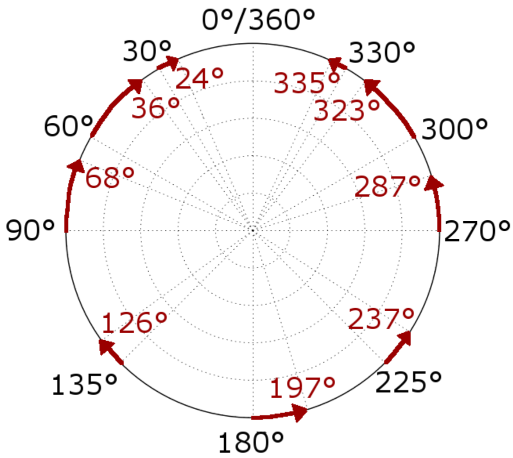


Figure 6. Relationship between communicated angle to go and mean reported angle.

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. The participants needed on average 8.63s to 12.73s to report the direction and distance. This also implies that they needed circa 3 to 4 rotations to make a decision as the time of circulation was 3 seconds.

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. 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.

	DurInt	DurRhy	DurRou	IntInt	RhyInt	MotInt
Mean deviation	50.5°	41.9°	39.1°	54.2°	37.5°	46.8°
Input time (in s)	8.63	7.94	8.91	12.73	8.82	9.82
Clear and understandable	4.00	3.91	3.55	2.55	4.09	3.36
Intuitive	4.00	3.82	3.64	3.18	3.91	3.45

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

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%. Also, this pattern placed second best when considering how clear and understandable distance was perceived. It additionally came second when considering the intuitiveness of the direction indication.

	DurInt	DurRhy	DurRou	IntInt	RhyInt	MotInt
Correct distance	90,3%	90,3%	59,7%	69,0%	95,8%	64,4%
Clear and understandable	3.82	4.55	3.09	3.36	4.09	3.36
Intuitive	4.00	4.27	3.18	3.55	4.00	3.36

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

Mental effort

When asked for their rating of 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*, *IntInt* and *MotInt* require a relatively high mental effort where *DurInt*, *DurRhy* and *RhyInt* performed best.

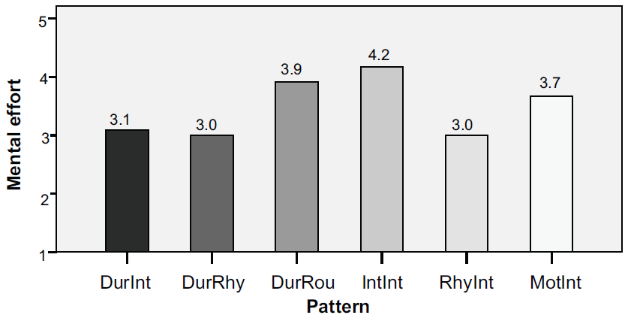


Figure 7. Average rating of perceived mental effort ranging from 1 – very low to 5 - very high.

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* and *MotInt* received 5 and 3 votes, respectively. 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 [22]. Van Erp and Van Veen, who tested vibrotactile feedback in cars [23], concluded from feedback of participants that time and training is needed to trust tactile information. Hoggan and Brewster [20] 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 53.3° in the first run to 37.1° in the last run.

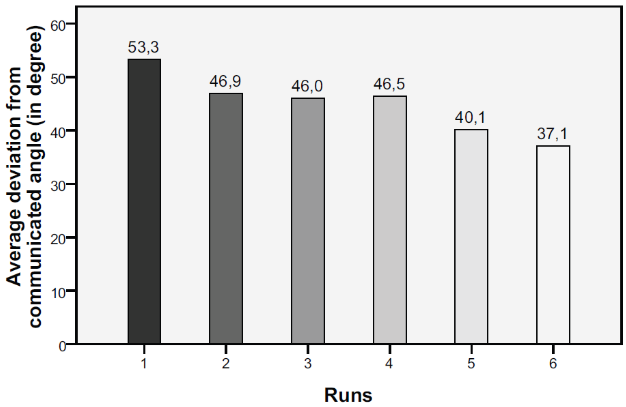


Figure 8. Effect of training on average deviation of reported from given angle.

This is a reduction of more than 30%. Pearson r for the correlation between order and deviation is -0.12. This indicates that the more participants became familiar with the vibrations, the smaller the error became. 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. Using motion to support the communication of the direction (as used in *MotInt*) is not beneficial as users commented that they were rather irritated by the changing intensity levels. This also made it complicated to identify the distance.

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.

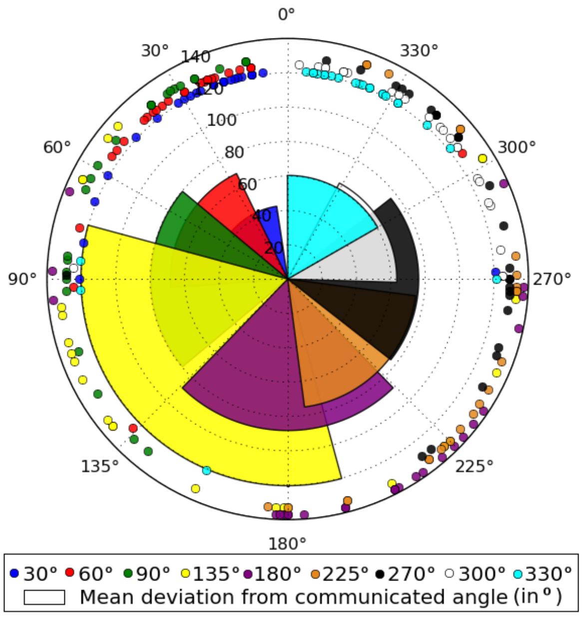


Figure 9. Location of reported angles and mean deviation of reported angles from indicated angles for *RhyInt*.

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.

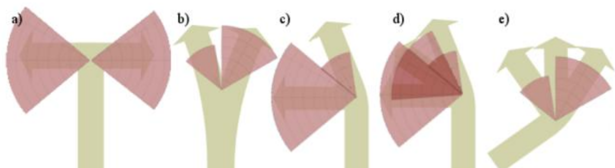


Figure 10. Practical implications of deviations of *RhyInt*.

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. due to this limited ability to convey a greater variety of directions (not just left and right) [15]. 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 with the mobile device [17]. 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.

PocketNavigator

PocketNavigator is a map-based pedestrian navigation application available in the Android market that also offers hands free navigation via tactile feedback [16]. It does provide turn-by-turn instructions but these are provided only when the user reaches the next turn. This is in contrast to most other turn-by-turn navigation systems, such as NaviRadar, where the user is informed in advance which direction one has to travel at the next crossing. 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 usage of Ovi Maps, which offers visual, tactile and spoken instructions to guide the users. Ovi Maps 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 Ovi Maps informs them via 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.

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. 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. All except one participant had experience with some form of vibration feedback, such as the vibration alarm when a mobile phone is in silent mode (92%), game controllers with vibration feedback (67%) or vibrations as touchscreen enhancement (58%). 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 *anonymized* which is occupied by many 5-floor student houses. It was selected because of its small size, high number of crossings, and its winding streets and lanes (see Figure 11). 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.

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.

Figure 11. Routes I-III on *anonymized* University campus.

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.

Procedure

Participants took part in the study individually. In the beginning, they were introduced in the purpose of the study:

the comparison of different pedestrian navigation systems. 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. Once the study was complete (circa 60-70 minutes from its commencement), participants received payment.

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 [18].

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.

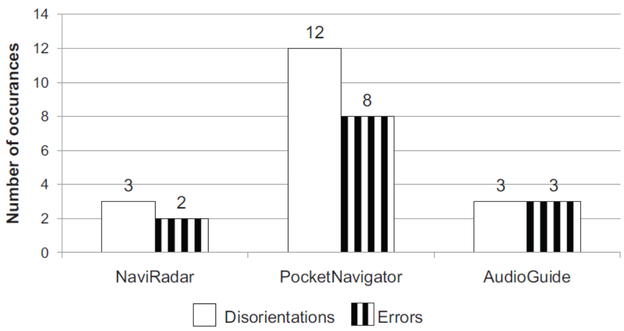


Figure 12. Overall count of errors and disorientation events for all participants.

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 usability satisfaction followed by NaviRadar and PocketNavigator. 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 an neutral to low task load for the other two. Furthermore, we asked the participants to state their first, second and third preference towards the three navigation techniques. Spoken instructions received on average place 1.3, NaviRadar 2.25 and PocketNavigator 2.4.

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. 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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