



Fakultät II – Informatik, Wirtschafts- und Rechtswissenschaften  
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# **Conveying Spatial Information for Navigation and Orientation with Tactile Displays**

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## Abstract

Keeping one's balance, staying oriented in an unfamiliar city, or finding a friend in a crowd, spatial information is essential to pedestrians on the move. Usually, our senses obtain the necessary information but they do not always suffice. For example, in a large parking lot it may be difficult to spot one's car. Recent advances in technology have enabled us to address these issues with location-based services, such as interactive maps on handheld devices or navigation systems for pedestrians. They provide spatial information far beyond what our senses are able to obtain.

However, for pedestrians interacting with location-based services usually involves handheld devices that can be used outside and on the move. In this context, users typically face three challenges. First, concentrating on the screen of a handheld device may *distract* users from the environment. For example, users might miss other traffic causing dangerous situations. Second, spatial information is typically provided in an abstract form. For example, reading a map requires mentally aligning its 2D content to the environment. Such abstract representations may be difficult to apply *efficiently*. Third, situation induced impairments may prevent users from *perceiving* the presented information in the first place. For example, sunlight reflections may leave the display unreadable or speech output may be missed when the environment is too noisy.

Models of processing sensory information predict that conveying information via the sense of touch is a promising approach to addressing these three issues. Therefore, this thesis investigates the tactile presentation of spatial information. We introduce the concept of *Spatial Tactons*, which means to encode the direction and distance of spatial entities (e.g. landmarks, people) in vibro-tactile stimuli. We explored two designs: a multi-actuator design where the actuators are attached to a belt worn around the waist by the user, and a single-actuator design using a common mobile phone's vibration alarm. We show that by creating vibro-tactile stimuli around the user's waist, the direction and distance of several landmarks or persons can be encoded with respect to the wearer's position and orientation. For encoding the distance we show that rhythm, intensity, and duration of a stimulus are feasible parameters. For single-actuator designs, we investigate encoding spatial information in rhythm patterns. We show that this approach enables users to effectively locate entities.

Reporting from six experiments, we argue that Spatial Tactons are suitable to overcome the above challenges. We show that if Spatial Tactons replace traditional visual user interfaces of navigation systems, they can diminish the user's distraction. Further, we show that we can enhance the efficiency of interpreting map-based spatial information by creating an additional sense of direction with Spatial Tactons. Finally, we show that the perception of Spatial Tactons is sufficiently reliable for them to be applied in distracting and cognitively challenging situations.



## Zusammenfassung

In einer fremden Stadt orientiert bleiben, einen Freund in einer Menschenmenge finden oder einfach das Gleichgewicht halten; räumliche Orientierung ist essentiell für Fußgänger. Unsere Sinne helfen uns bei der Orientierung, reichen jedoch nicht immer aus. Es kann z.B. schwierig sein, sein Auto auf einem großen Parkplatz zu finden. Neue Technologien, wie Ortsbasierte Dienste oder interaktive Karten auf mobilen Endgeräten können uns helfen, diese Einschränkungen zu überwinden. Sie stellen die räumliche Information bereit, die unsere Sinne nicht mehr liefern können.

Diese Dienste bedingen jedoch oft, dass Fußgänger unterwegs mit mobilen Endgeräten interagieren. Dadurch ergeben sich drei Herausforderungen. Erstens kann die Interaktion mit mobilen Endgeräten während des Laufens den Nutzer ablenken. Im Straßenverkehr kann dies dazu führen, dass der Nutzer einen Verkehrsteilnehmer übersieht. Zweitens wird räumliche Information meist in abstrakter Form, z.B. eine Karte präsentiert. Eine Karte muss jedoch mental rotiert werden, damit sie auf die Umgebung angewendet werden kann, was es erschweren kann, die räumliche Information effizient anzuwenden. Drittens können so genannte situationsbedingte Einschränkungen die Wahrnehmung der räumlichen Information verhindern. Wenn z.B. Sonnenlicht das Display trifft, können die Reflexionen das Display unlesbar machen.

Wissenschaftliche Modelle menschlicher Informationsverarbeitung sagen vorher, dass die Vermittlung von Information über den Tastsinn ein möglicher Ansatz ist, diese Herausforderungen zu adressieren. Diese Dissertation untersucht die taktile (=den Tastsinn betreffende) Präsentation räumlicher Information. Sie führt das Konzept Spatial Tactons ein: die Kodierung von Richtung und Distanz räumlicher Entitäten (z.B. Landmarken oder Personen) in vibro-taktilen Stimuli. Wir untersuchen zwei Ansätze: einen taktilen Gürtel, bei dem mehrere Vibrationsaktuatoren um die Hüfte verteilt getragen werden, und einen einzelnen Vibrationsmotor, wie man ihn in Mobiltelefonen findet. Wir zeigen, dass Vibrationsstimuli, die um die Hüfte herum erzeugt werden, es ermöglichen, effektiv Distanz und Richtung mehrerer räumlicher Entitäten in Relation zur Position und Ausrichtung des Trägers zu vermitteln. Wir zeigen, dass Distanz wahlweise in den Parametern Rhythmus, Frequenz und Dauer des Vibrationsstimulus kodiert werden kann. Für einzelne Aktuatoren zeigen wir, dass Distanz und Richtung einer räumlichen Entität effektiv in Rhythmusmustern kodiert werden kann.

Basierend auf den Ergebnissen aus sechs Experimenten argumentieren wir, dass Spatial Tactons die aufgezeigten Herausforderungen adressieren können. Die Ergebnisse zeigen, dass Spatial Tactons Ablenkung reduzieren können, wenn sie visuelle Nutzungsschnittstellen ersetzen. Weiterhin zeigen wir, dass Spatial Tactons als eine Art Orientierungssinn eingesetzt werden können, der es Nutzern erlaubt, Karten effizienter zu interpretieren. Außerdem zeigen wir, dass Spatial Tactons auch in Situationen mit hoher sensorischer und kognitiver Last zuverlässig interpretiert werden.





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# Table of Contents

<b>1</b>	<b>Introduction</b>	<b>1</b>
1.1	Challenges: Distraction, Efficiency, Perception . . . . .	3
1.2	Approach: Presenting Information via the Sense of Touch . . . . .	7
1.3	Research Questions and Contribution . . . . .	11
1.4	Structure . . . . .	12
<b>2</b>	<b>Fundamentals</b>	<b>15</b>
2.1	Spatial Information . . . . .	15
2.2	Tactile Information Presentation . . . . .	18
2.3	Rel. Approaches on Presenting Spatial Inf. with Tactile Displays . . . .	27
<b>3</b>	<b>Encoding Spatial Information in Spatial Tactons</b>	<b>35</b>
3.1	Encoding Location with Multiple Actuators (Tactile Belts) . . . . .	36
3.2	Encoding Location with a Single Actuator (Tactile Compass) . . . . .	49
<b>4</b>	<b>Reducing Distraction in Turn-by-Turn Wayfinding</b>	<b>57</b>
4.1	Background and Motivation . . . . .	57
4.2	Creating a Tactile Wayfinder with a Tactile Belt . . . . .	59
4.3	Eyes-Free Pedestrian Navigation with a Tactile Compass . . . . .	73
<b>5</b>	<b>Increasing Efficiency of Map-Based Navigation</b>	<b>89</b>
5.1	Background and Motivation . . . . .	89
5.2	Supporting Paper Map-based Navigation with a Tactile Belt . . . . .	91
5.3	Supporting Map-based Navigation with a Tactile Compass . . . . .	106
<b>6</b>	<b>Improving Perception of Spatial Information</b>	<b>117</b>
6.1	Background and Motivation . . . . .	117
6.2	Where is my Team? Supporting Situation Awareness with a Tactile Belt	118
6.3	Keeping Groups Together with a Tactile Compass . . . . .	130
<b>7</b>	<b>Conclusions</b>	<b>139</b>
7.1	Contributions . . . . .	139
7.2	Limitations . . . . .	143
7.3	Applying Spatial Tactons . . . . .	145
7.4	Future Work . . . . .	146



# 1 Introduction

Being aware about space and the location of objects within space is a key aspect of human life. Without being able to behave according to space and how the entities within it are located humans, would not be able to conduct most common activities. Thus, many of our senses are able or even dedicated to obtain spatial information. Our two ears and two eyes enable us to estimate size, distance, and location of entities in space. Our tactile system, the sense of touch, is able to detect touches on the body and to explore the spatial characteristics of objects. Our sense of balance prevents us from falling over when standing upright. Our vestibular system tells us how our body is accelerated and how it is oriented with respect to gravity. Our proprioceptive system keeps us informed about the posture of our limbs with respect to the body. Thanks to these senses we can walk upright, grab objects, move through our environment in a coordinated way, avoid natural enemies, locate and gather food, and find our way back home. Many of these tasks become possible because our senses inform us about the location of relevant entities in space, such as the location of landmarks we use for navigation, objects we are interacting with, or people that accompany us.

Yet, our senses are limited. As illustrated in Figure 1.1<sup>1</sup>, we are not always able to perceive the location of entities in space that are relevant for a given task. Imagine trying to find your friends in a dense crowd of people. Imagine being a hiker in a national park strayed away from the marked paths who lost the sense of orientation and starts walking in circles. Imagine getting off a bus after sunset in a foreign city and having difficulties to recognise any landmark in the darkness. In all three situations our senses are not sufficient to obtain the necessary spatial information. The lack of reference points, landmarks, or the sense of direction will make it difficult to remain spatially oriented.

Thus, mankind has invented a number of tools that extend and complement our natural senses. A few examples are shown in Figure 1.2<sup>2</sup>. One of the oldest tools are maps. They show an abstract version of geographic features while preserving their spatial relation. Archaeologists have found maps that are older than 5,000 years. A Song Dynasty book from 1040 AD mentions a "south-pointing fish" [Tem86] and is the first evidence for what we today know as a compass. A compass provides a sense of the Earth's magnetic field which humans are not able to sense naturally. Further, many civilisations took great effort in deploying landmarks in the environment, ranging from early light houses in order to guide ships safely along the coast to today's streets, which are all uniquely labelled with street signs. In the last decades, a lot of effort was put into developing and deploying satellite systems, such as GPS, Glonass, or Galileo, that allow obtaining one's location with a precision of a few metres at any place of the world. Most of these tools

<sup>1</sup> Image sources: Wm Jas, Crowded Street, Oct 9, 2005, via Flickr, CC BY SA 2.0 (left), Ari Helminen, Snowy Forest, Nov 18, 2010, via Flickr, CC BY 2.0 (mid), Marcelo Jorge Vieira, Gray City, Apr 18, 2006 via Flickr, CC BY 2.0 (right).

<sup>2</sup> Image sources: Calsidyrose, Compass Study, Aug 21, 2010, via Flickr, CC BY 2.0 (mid), NASA, public domain (right)



*Abbildung 1.1: Our senses are our primary means of obtaining spatial information sufficient for most tasks. However, when finding friends in a crowd, maintain one's orientation in a dense forest, or finding one's way through a foreign city they might not be able to provide the necessary information.*

are designed to provide the location of spatial entities as a reference, such as Magnetic North or salient geographic features.

Recently, the invention of global, satellite-based navigation systems, comprehensive geographic databases, and powerful, always-connected handheld devices, has enabled a whole new category of tools called location-based services. As illustrated in Figure 1.3, we now have interactive maps which indicate our position and orientation automatically. Navigation systems provide turn-by-turn navigation instructions to safely guide travellers to destinations they have never visited before. Friend finders, such as Google Latitude<sup>3</sup> or Yahoo Fireeagle<sup>4</sup> even allow us to keep track of the whereabouts of our friends in real-time. An integral part of all of these systems is to communicate the location of spatial entities to the user.

These services are becoming increasingly more common for many tasks in everyday life, car navigation systems being one of the most prominent examples. However, unlike traditional personal computers, location-based services often run on handheld devices, which can be used anywhere and in many kinds of situations. For example, walking significantly impairs our ability to interact with mobile devices [KWS08]. Also, freezing cold may impair our motor skills or loud noise may impair our hearing. Thus, traditional user interface concepts may not suffice to ensure a safe, effective, and satisfactory usage experience. Therefore, new approaches of conveying spatial information are needed to

<sup>3</sup> <http://www.google.com/latitude/>

<sup>4</sup> <http://fireeagle.yahoo.net/>



Abbildung 1.2: Since our senses are limited, we have invented a number of tools, such as maps (a), compasses (b), or satellite navigation systems (c), to extend our perception beyond them.

accommodate the challenging usage of location-based services on the move as a person that is exposed to "the wild".

The scope of this thesis is to investigate how to design user interfaces for location-based services that communicate essential spatial information to pedestrians on the move in a way that addresses these challenges.

## 1.1 Challenges: Distraction, Efficiency, Perception

When a traveller uses a location-based services to navigate through his environment, models of information processing (see Erp [vE07] p.12 ff) typically include three phases: sensing/perceiving a stimulus, comprehending the stimulus, and executing an action. Hence, first, the information has to be *perceived* which means it has to make its way from the device to the human brain. Second, the information has to be applied by the brain to the current task. If the perceived information is in an inappropriate format its interpretation can consume a lot of cognitive resources and may lead to lower task *efficiency*. Third, the emitted information may draw the users' attention to the device too much. In such case, the users may become *distracted* and may not notice important events around them. These challenges are elaborated in the following.



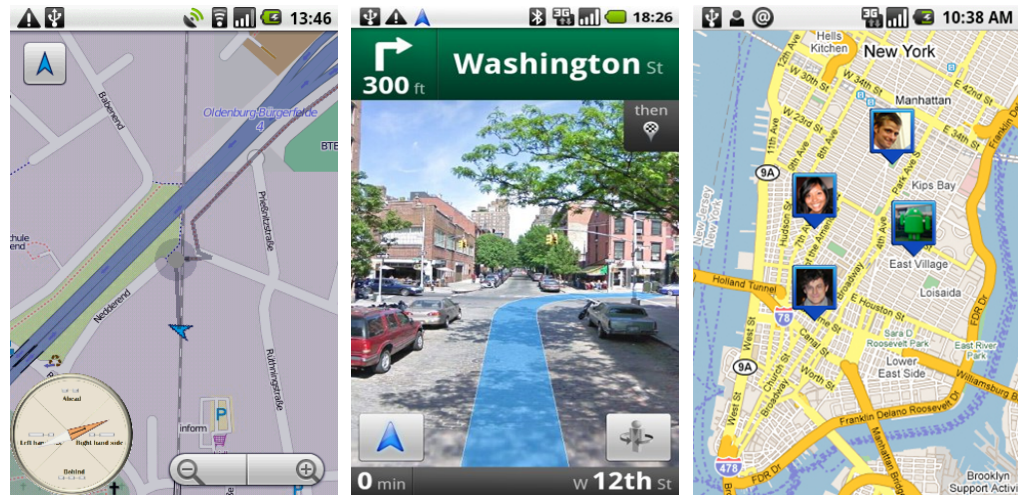


Abbildung 1.3: Recent advances in technology have enabled location-based services, such as interactive maps (a), navigation systems (b), or friend finders (c), that allow obtaining spatial information far beyond the capabilities of our senses.

### 1.1.1 Distraction

With *distraction* we refer to the state of being distracted, i.e. the lack of attention on something that should be focussed. If users of location-based services become distracted in traffic, this may lead to dangerous situations.

When location-based services are used on the move, distraction can be caused by the users' need to shift their attention towards the mobile device. They need to look at rather tiny displays to check the map or they have to listen carefully in order to not miss turning instructions.

To cope with the need to shift attention, pedestrians on the move usually interact in short bursts with mobile devices only [OTRK05]. This leads to a significant fragmentation of the user's attention. According to a study by the Pew Research Center [MR10] one in six (17%) cell-owning adults say they have physically bumped into another person or an object because they were distracted by talking or texting on their phone.

Auditory interfaces may be a solution here as they allow eyes-free interaction. Still, there is the problem of how to present auditory signals to the user. When using speakers, they have to be turned loud enough so the user does not miss any signal. However, users may feel embarrassed if others in their vicinity are able to hear the signals, too. In some cultures or situations it may also be socially inappropriate to "pollute" the environment with noise.

Ear plugs may solve this problem, as the auditory content can only be heard by the wearer. Ear plugs, however, may block off environmental noise. This may lead to the



*Abbildung 1.4: Challenge distraction: the communication of the spatial information distracts the user from the environment.*

iPod Zombie Trance", which refers to the loss of situational awareness from listening to loud audio content. According to the Sydney Morning Herald<sup>5</sup>, authorities in Australia are speculating that this might be a contributing factor to the still increasing pedestrian fatalities. So, being distracted by common screens and ear-plugs are non-negligible issues for the use of mobile applications in general and location-based services in particular.

### 1.1.2 Efficiency

With *efficiency* we refer to the amount of effort, such as time or thought, required fulfil a given task. In the scope of this thesis this refers to the effort required to understand the spatial information delivered by a location-based service and apply it in a meaningful way.

There are a number of issues that can impede the efficient processing of spatial information. For once, many location-based services are based on maps. One problem that is shared by all forms of maps is that their abstract geographic content has to be interpreted before being applied to the real world. The content of the map has to be aligned to the

<sup>5</sup> <http://www.smh.com.au/digital-life/mp3s/pedestrian-death-rise-blamed-on-ipods-20100905-14w4d.html>

environment [AW92]. The existence of this so called *alignment effect* has been proven by e.g. Tamura et al. [TSI02]. The alignment effect explains why people rotate the map until it fits with the current orientation, and predicts that reading un-aligned maps will result into more errors. Rotating maps according to the environment improves user's performance in wayfinding [WHW07, StBNL08]. On the other hand, rotating maps decreases the ability to build up a cognitive map of the environment [WLPO96].



Abbildung 1.5: Challenge efficiency: the spatial information is communicated in a way that is difficult to interpret.

Another problem is that today's maps do not convey the type of information that people naturally use to communicate spatial information. The human's common approach is describing one's location by relating it to a landmark, e.g. "next to the exhibition hall". This is typically used in verbal descriptions [MRBT03, RMT04, DMT06]. The problem here is that landmarks must be known or recognizable, which may technically be difficult to achieve. That is why location-based services often use geocentric presentation to convey spatial information, e.g. by highlighting routes or POIs on a map. However, interpreting maps requires skills and creates mental workload, since the maps' geocentric spatial information has to be interpreted and aligned to the environment [AW92].

Field studies confirm that using maps for navigation is a difficult task for many people [IFIO08]. By adding turning instructions to the map, modern navigation systems make

navigation easier. The disadvantage of this information presentation is that it disengages users from the environment [LVR<sup>+</sup>08] and impedes understanding the environments. Turning instructions also lead to less spatial knowledge than maps [ASB<sup>+</sup>06]. Turning instructions may also be difficult to apply. For example, in the beginning of a tour, Google Maps Navigation issues the first turning command by announcing towards what street to head, such as "Start west from Wellington Lane towards Waterloo Street". Users who do not know where West is in this situation or who are not familiar with the streets cannot make sense of such instructions.

### 1.1.3 Perception

With *perception* we refer to obtaining information from the human senses and its interpretation in the brain. Location-based services are of no use if the information they present cannot be perceived.

The ability to perceive information from a mobile device may be impeded by several factors. First, mobile devices still offer only limited display capabilities [WHW07, IFIO08]. If the screen is held too far away, the resolution becomes too small for many people to still be able to read it. If the screen is tilted or in case of (sun)light reflections, it may even become impossible to read the screen at all. At night, the stark contrast between the dark environment and the bright screen requires the eyes to adjust to either of these, which usually takes a few seconds. Auditory information may be difficult to perceive if there is a lot of noise, e.g. by traffic or loud music.

In general, if a sense is already under high workload, it becomes difficult to process additional information through that sense [Wic02, vE07]. For example, while it is possible to listen to music while cleaning the flat, it is rather difficult to listen to music and listen to a person speaking at the same time. Hence, reading a mobile device's display or listening to spoken instructions while paying attention to traffic concurrently can be difficult.

## 1.2 Approach: Presenting Information via the Sense of Touch

In summary, we have identified three challenges of consuming spatial information from a handheld device:

- When interacting with the handheld device users may become *distracted* from the environment, so that their attention towards important events, such as an approaching car, is impeded.
- The information has to be presented in a suitable manner that allows to *efficiently* apply the presented spatial information to the current task. Since location-based ser-





Abbildung 1.6: Challenge perception: the spatial information is communicated by a sense that is temporarily or permanently impaired.

vices often rely on maps, and these suffer from the alignment effect, this may not always be the case.

- Since location-based services are often used outdoors and on the move, the interaction may suffer from situation induced impairments. Thus, users may not be able to *perceive* the presented spatial information anymore.

This section analyses the cause of above challenges with the help of findings from basic perceptual research and argues that conveying information via the sense of touch is a potential approach to addressing these challenges. The challenges can be explained by the fact that the human's resources to perceive and process information are limited. As a task becomes more demanding, e.g. when navigating through lively traffic, the resources left in reserve decrease. When resources are exceeded, a decline in performance is the consequence. Further, if there is more than one task, e.g. additionally consuming navigation information from a mobile device, resources have to be shared between these tasks.

Early theories assumed the concept of a single channel bottleneck and suggested that time was the limiting resource, which could not be shared between the tasks [Wel67].

The idea was that for each task a single "central processor" had to be shared, much like single core computers do to process tasks in parallel.

However, the single resource theory was discarded in favour of a multiple resource theory, as studies showed that adding a second task will not result in half the performance for each of the tasks [AAR72, Wic84]. Instead the findings indicate that different types of tasks have different resource pools. Tasks tapping into different resource pools will be less likely to cause an overload, such as missing an obstacle in the environment or missing a navigation instruction issued by the mobile device. Wickens [Wic84] proposed that resources are split amongst several dimensions, such as sensory modality (visual, auditory, tactile), stage (perception, processing, action), or reasoning (subconscious, symbolic, linguistic). Performance decrease depends on to what extent the tasks compete for the same resources. These dimensions can be explained by the underlying neurophysiological mechanisms in the brain. Visual signals are processed by a different part of the brain than audio or tactile signals.

In particular, Wickens [Wic02] proposed the four dimensional Multiple Resource Model (MRM). The four dimensions are stages (perception & cognition, responding), perceptual modalities (visual, auditory), visual channels (focal, ambient), and processing codes (spatial, verbal). This model would for example predict that route guidance is better provided as speech (auditory, verbal) than presented as text (visual, verbal), as driving is already a visual, verbal task.

One limitation of the Multiple Resource Model to be considered is that it assumes all tasks to be alike. However, taking a map as example, a very simple street map will be easier to use in the car than aerial images, although both times reading the map is a visual, spatial task. MRM can only predict relative differences in task interference when the different configurations are sufficiently similar in terms of difficulty. Also shared goals are an issue. For example, navigating and talking about what turn to take next is less challenging than navigating and talking about what meal to cook in the evening.

Further, there are tasks which are considered "pre-attentive". These tasks may not use any resources and hence not cause task interference. In his thesis, van Erp [vE07] introduces the *Prenav Model*, which indicates that bypassing the *cognitive ladder* is the key to avoid exceeding cognitive resources. The Prenav model is a workload model tailored to a human operating a platform. A platform can be any steerable object, ranging from cars, helicopters, or bicycles to the human walking him/herself. Derived from the Multiple Resource Theory and other workload models, Prenav introduces the *sensation* → *perception* → *decision* → *actionloop*. In contrast to Wickens, van Erp distinguishes between sensation = detection of external events by sensory receptors and perception = interpretation of sensory input by the brain. To avoid generating cognitive effort by an information presentation, Prenav suggests two shortcuts. The first is closing the *sensation* → *actionloop*, which refers to presenting information in an intuitive manner, which does not require any kind of thinking. An example would be keeping one's balance, which requires immediate action based on the input from the eyes (visual

system), ears (vestibular system) and the body's sense of where it is in space (proprioception). The second shortcut is closing the *perception*  $\rightarrow$  *actionloop*, which refers to automated if - then"rules. An example would be an experienced driver stopping at a red light.

These theories suggest that above challenges can be addressed by presenting information in a suitable way. To address the challenge of *distraction*, information should be presented via a sensory modality which is not used to attend to the environment. The challenge of *efficiency* can be addressed by finding an intuitive representation that closes the *sensation*  $\rightarrow$  *actionloop* or the *perception*  $\rightarrow$  *actionloop*. The *perception* of relevant elements can be ensured by communicating information via senses that are not overloaded with processing environmental information.

During navigation and orientation, the sense of vision is the primary sense to stay aware of the environment. Besides, the sense of hearing helps to spot e.g. traffic participants that are not in the field of view, such as a car approaching from behind. Thus, travelers may benefit from freeing the senses of vision and hearing and convey information via a different sense. Findings from previous research suggests that the sense of touch might offer a suitable channel of communication that would allow addressing all three challenges.

Regarding the challenge of *distraction*, we exploit the fact that we mostly use our ears and eyes to perceive our environment. For example, when we are navigating through a busy place, we use our eyes to evade obstacles and other people. Our ears allow us to perceive objects beyond our field of vision, such as a fast cyclist approaching from behind. The sense of touch is, however, hardly used to attend to the environment. According to Wicken's Multiple Resource Theory, communicating information via the sense of touch will be less likely to interfere with our senses of vision and hearing. If we manage to keep the haptics in the ambience [Mac09] we may even be able to communicate information pre-attentatively, so it will not interfere with the primary task at all. Thus, users are more likely to remain able to focus on the environment.

The challenge of *efficiency* can be addressed by the fact that the skin is inherently spatial and is subconsciously used to process spatial information. For example, a person can intuitively name the location of a touch on the skin, which is an important ability, given that the touch could be a mosquito or the paw of a wild, hungry animal. Studies have shown that we can intuitively construct a pointing direction from such a perception [vE05a]). A longitudinal study by Nagel et al. [NCK<sup>+</sup>05] also suggests that processing spatial information through vibro-tactile stimulation can become subconscious and even act like an additional sense, dramatically changing the subjects perception of the whole world. Exploiting these human capabilities might allow closing the sensation, action loop or the perception, action loop and, thus, creating highly intuitive interfaces conveying spatial information.

Finally, the challenge of *perception* is addressed by the fact that most situation induced impairments concern the sense of hearing and the sense of vision. Our eyes are impaired

due to sunlight reflections on the display, or we find it hard to adjust to the brightness of the display when it is used in darkness. Our ears may not be able to hear spoken navigation instructions due to the noise of a construction site or a crowd of people around us. The sense of touch, however, is hardly affected by these interferences and it is hardly used to obtain information about the environment. Hence, we are more likely to perceive information conveyed by the sense of touch, when our eyes and ears are temporarily impaired or nearing perceptual overload.

Therefore, this thesis investigates how to encode spatial information via the sense of touch in the domain of location-based services and handheld devices, which are used on the move.

### 1.3 Research Questions and Contribution

This section outlines the research questions addressed in this thesis and will highlight the main contributions. The central contribution of this thesis is to show how spatial information can be encoded in tactile user interfaces and to prove that this allows addressing the three challenges (perception, efficiency, distraction).

**RQ1 (Fundamentals): What is the state of the art in encoding spatial information in tactile user interfaces?** Chapter 2 analyses the fundamentals of encoding spatial information with tactile user interfaces. In Section 2.1, we argue that for location-based services the best way is to encode the direction and the distance of a spatial entity with respect to the user's location and orientation. To understand the design space of encoding information via the sense of touch, we review the fundamentals of cutaneous perception and tactile information presentation in Section 2.2. We argue that body location, duration, rhythm, and the combined use of amplitude and frequency (referred to as intensity in the following) are suitable parameters. Reviewing related work in Section 2.3, we show that encoding spatial direction in the body location of a tactile stimulus using multi-actuator displays has proven to be a feasible approach. We conclude that there are three things missing: how to encode the location plus additional information of multiple entities, which parameter is best to encode spatial distance, and how to encode spatial directions with single actuator displays.

**RQ2 (Spatial Tactons): How can spatial information be encoded by tactile user interfaces?** In Chapter 3, we fill these gaps by advancing previous work on encoding spatial information with tactile user interfaces. We introduce the term *Spatial Tactons*. Tactons [BB04] are abstract, structured messages that encode multidimensional information. Spatial Tactons refers to Tactons that encode the direction and distance of one to several spatial entities. In Section 3.1, we show that the location of several spatial entities can be encoded by presenting them in sequential order. We also show that spatial distance can be encoded in the duration, rhythm, and intensity of a stimulus. In Section 3.2, we provide evidence that directions can be encoded in rhythm patterns, too, and that this can be combined with encoding spatial distances in the pause between two patterns.



**RQ3 (Distraction): Will Spatial Tactons lower the user's level of distraction?** Having shown that it is possible to encode spatial information in Tactons, the question remains how well these Tactons perform against established visual user interface concepts. If above Tactons are too complex, the advantages gained from communicating spatial information through an idle sense may be negated by the increased cognitive resources needed to interpret them. In Chapter 4, we report from two studies where two types of Spatial Tactons were used to provide directions in a pedestrian navigation system. Based on our findings, we argue that replacing visual interfaces of navigation systems by Spatial Tactons can successfully address the challenge of distraction.

**RQ4 (Efficiency): Will Spatial Tactons increase the user's navigation efficiency?** Studies of navigation systems and navigation strategies have repeatedly come to the conclusion that turn-by-turn instructions are not the most suitable form to provide navigation support to pedestrians. It has been argued that turn-by-turn instructions are disengaging the traveller [LVR<sup>+</sup>08], lead to worse spatial understanding [ASB<sup>+</sup>06], or not necessarily more efficient than maps [IFIO08], and are considered as curbing [PB10b]. Therefore, in Chapter 5, we propose and investigate an alternative form of navigation support that is enabled by Spatial Tactons. We show that instead of providing fine-grained navigation instructions, it can be equally effective to combine map-based navigation with conveying the general direction of a landmark, such as the travel destination. We argue that Spatial Tactons used in this way allow addressing the challenges of efficiency and distraction, by making it easier to interpret and apply the contents of the map, and by encouraging travellers to check the map less often.

**RQ5 (Perception): Can Spatial Tactons be perceived despite high perceptual and cognitive load?** Finally, we address the challenge of perception. We have argued that if senses are under high workload it becomes more difficult to process more information. Still, communicating information via the sense of touch may be feasible since it is often "idle". Therefore, in Chapter 6, we argue that Spatial Tactons can be used in situations with high perceptual and cognitive workload and will be able to measurably increase the user's awareness of the situation.

## 1.4 Structure

This section explains the structure of the thesis. Each research question from the previous section is addressed by one chapter. Figure 1.7 illustrates which chapter addresses which research question.

Chapter 2 reviews fundamental work on the mental representation of spatial information and encoding information via the skin. It also reviews related approaches of encoding spatial information with tactile displays.

Chapter 3 introduces Spatial Tactons: short, abstract messages that communicate spatial information in the different parameters of a vibro-tactile stimulus.

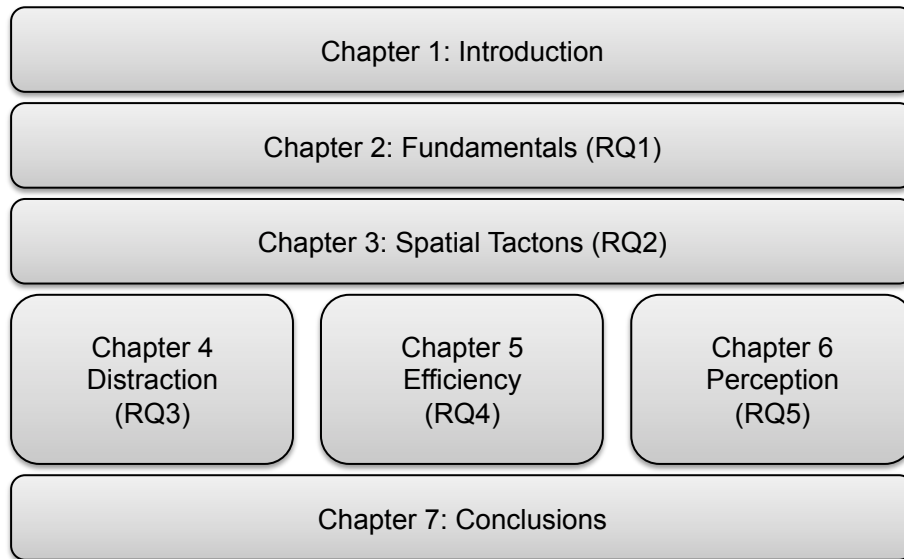


Abbildung 1.7: Illustration of the thesis structure

The subsequent chapters 4, 5, and 6 will present six field experiments that investigate to what extent Spatial Tactons allow addressing challenges of *distraction*, *efficiency*, and *perception*.

Chapter 4 investigates the applicability of Spatial Tactons for turn-by-turn navigation. This chapter will focus on the challenge of *distraction*.

Chapter 5 explores a novel form of navigation support enabled by Spatial Tactons. Instead of providing turn-by-turn instructions, Spatial Tactons are employed to create a novel sense of direction to support map-based navigation. This chapter will focus on the challenge of *efficiency*.

Chapter 6 examines the use of Spatial Tactons to improve situation awareness. Spatial Tactons are used to continuously communicate the location of people in environments where high perceptual workload is a common problem. Hence, this chapter will focus on the challenge of *perception*.



## 2 Fundamentals

This section reviews the fundamentals required to understand how spatial information can be encoded with tactile displays. First, it reviews how the human brain organises spatial information to derive what information should therefore be encoded (2.1). Second, it analyses the fundamentals on encoding information via the sense of touch (2.2). Finally, it reviews previous approaches on encoding spatial information in tactile displays (2.3).

### 2.1 Spatial Information

In order to communicate spatial information efficiently it is important to understand how it should be represented. Therefore, this chapter reviews the fundamentals of spatial information, how it is stored in the brain, and how it is applied to navigation and orientation scenarios.

#### 2.1.1 Spatial Knowledge Representation

Knowledge about the environment can be divided into three types of mental representations [Law94]: *landmark knowledge*, *route knowledge*, and *survey knowledge*.

*Landmarks* are objects that stand out from the environment and therefore can easily be recognized and remembered [Pla05]. Landmarks can be used as reference points for navigation and exploration. They help to apply existing spatial knowledge to the environment [Gol98] and therefore aid spatially oriented behaviour, which is essential for any navigational task.

*Routes* can be considered as a possible connection between two or more locations [Pla05]. Route knowledge therefore comprises locations and connections between them, and therefore can be used to get from one place to another. Route knowledge is ego-centric, which means that actions at decision points require the person to be oriented in a specific way. Route knowledge can be externalised by creating route instructions. Those can, for example, be found in navigation systems in the form of: "in fifty metres turn left". Studies show that people mainly rely on landmarks if they generate external route instructions [MRBT03, RMT04, DMT06], such as verbal descriptions of a route. Landmarks are usually used to associate turning-instructions with recognisable places, as for example in "turn left at the church, walk past the supermarket, and turn right at the bakery".

*Survey knowledge* can be considered as a map-like representation of spatial information. In contrast to above representations this preserves the spatial relations between landmarks, places, roads, and other spatial entities [PRE00]. In the brain these spatial relations are usually stored in the form of cognitive maps [DS73]. However, cognitive

maps are oftentimes not very accurate [PR04]. Typically, humans simplify facts about the environments to make cognitive maps easier to process. Rivers and roads are rectified, crossings are considered perpendicular, and areas are aligned north-south or east-west. Well-known areas, such as salient landmarks, often take more space in the mental representation than unknown areas. Survey knowledge is more robust and flexible for navigation and exploration, as it allows people to identify shortcuts or recover from navigational errors. In above example survey knowledge would allow the traveller to understand that it might be also possible to walk straight at the church and turn left at the following junction.

As landmarks are the predominant form of mental representations of spatial information, and since they are usually used in communicating spatial information, this thesis will focus on presenting the location of point-type spatial entities. However, since survey knowledge is the most powerful and flexible representation of spatial knowledge, it is important to also communicate the spatial relations between these landmarks / spatial entities. Thus, we need to understand how point-type locations can be encoded and communicated.

### 2.1.2 Geocentric and Egocentric Representation

Space is boundless and relational. Hence, no absolute locations exist. In order to encode and communicate a location it has to be embedded into a stable reference system. An example is a WGS-84 coordinate which provides a location on Earth's surface in relation to the equator (latitude) and the Prime Meridian passing through the Royal Observatory at Greenwich (longitude). Typical reference systems are geocentric and egocentric [How66].

Geocentric representation of spatial information is defined as the way an object or a person is facing with respect to objects on Earth's surface, such as in the example above. A person's orientation can be altered by rotating around the body axis and movement in space. Being well orientated refers to the ability to behave tolerably correct according to the actual orientation, whereas if that is not the case, we person is considered to be disoriented. Geographic orientation comprises being able to walk a straight line, maintain a sense of orientation, or pointing to distant places. Geographic orientation skills fall into two classes: the ability of a person to maintain a sense of direction when moving in unknown environments and task requiring prior intellectual knowledge, such as pointing north or drawing a map.

Egocentric representation, in contrast, implies the positioning of an object or a body part with respect to some axis or plane defined entirely with respect to the body, or parts of it, of the observer. Fundamental to the problem of the egocentric orientation is the concept of the egocentre. It was introduced by Roelofs [Roe59] to describe that centre, fixed with reference to the body, from which absolute directions are judged, such as straight ahead, left, or upwards. There is no clear definition about the location of

the egocentre. Previous studies about egocentric judgment of directions suggest that the egocentre is located in the mid-traverse plane (around the mid-body or Z axis).

Egocentric representation has the advantage that it does not require knowledge about any external reference system, such as WGS-84 or the geographic layout of the major streets of the city. The only reference required is the person itself. Since the scope of this thesis is to design interfaces for location-based services, the location and orientation of the user can always be inferred from the used handheld device. Thus, this thesis focuses on egocentric representation of spatial information.

### 2.1.3 Encoding Location's from an Egocentric Perspective

Presenting locations' from an egocentric point of view requires understanding how these locations can be encoded.

According to Howard and Templeton [How66] *the fundamental geometrical concepts to express spatial information are two lines in a plane, the sign of rotation of a point moving about a fixed point in the plane, and the polarity of the line, i.e. the sign of movement along the line* 2.1. In more simple words, a location can be expressed by its direction and distance in relation to the location and orientation of a reference point. In the scope of this thesis this reference point would be the user. Thus, we need to encode the direction and distance of a landmark in relation to the user's position and orientation.

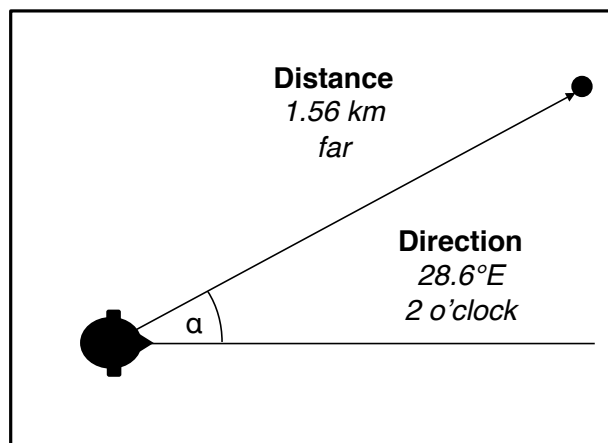


Abbildung 2.1: Fundamental geometric concepts required to express spatial information from an egocentric perspective: direction and distance

Furthermore, we have argued that preserving spatial relations between landmarks is important, since these then become survey knowledge and are most flexible and powerful for navigation and orientation tasks. Hence, we propose conveying the location of multiple landmarks from the user's egocentric perspective as a form to provide survey knowledge. Knowing the location of a single landmark may allow to reach the given

landmark, but it will not allow to understand one's exact location on a map. This unambiguity can be resolved by conveying the location of several landmarks at a time. This allows users to triangulate their position with respect to the landmarks and keep track of their location as they move around.

#### 2.1.4 Summary

For navigation and orientation humans rely on three types of spatial information representations: landmark knowledge, route knowledge, and survey knowledge. Survey knowledge is the strongest as it is most robust and flexible for navigation and exploration. Yet, people often use landmarks to communicate spatial information. Locations of e.g. landmarks can be expressed geocentrically or egocentrically. For a location-based service the egocentric representation has the advantage that the user's body serves as the frame of reference and, thus, no knowledge about the environment is required. From an egocentric perspective, a location can be expressed through its direction and distance in relation to the user's location and orientation.

Thus, the question is how to encode spatial direction and distance in relation to the human body via the sense of touch. Furthermore, to enable navigation and exploration by survey knowledge the direction and distance of several landmarks have to be conveyed at the same time.

## 2.2 Tactile Information Presentation

In order to understand how direction and distance can be encoded via the sense of touch, the basics of haptics and the resulting design implications have to be understood. Haptics serves as umbrella term for kinaesthetic (knowing one's orientation in relation to the gravity vector or other reference systems), proprioception (knowing the relative location of the body and the limbs) and cutaneous perception (perception via the skin).

Cutaneous perception can be separated into sensations of pressure, stretch, vibration, and temperature. In some cases, pain is considered a cutaneous sensation as well, although it can also be considered as an excessive stimulation of the four parameters above. This thesis focusses on vibration, i.e. mechanical oscillations created on the skin, since this type of stimulation is researched best for presenting information via the sense of touch. These interfaces are often referred to as vibro-tactile user interfaces.

In the following we review fundamental work on the the capabilities and limitations of the cutaneous perception. The goal is to understand how to encode information in vibro-tactile stimuli and what actuator technology is available.

### 2.2.1 Encoding Information with Vibro-Tactile Displays

A haptic stimulus can usually be decoupled into a number of parameters. For example, as any oscillating wave, a vibration stimulus has a frequency, an amplitude, and a waveform.

Van Erp [vE02] identifies four parameters that are relevant when applying vibration directly to the skin. He names *subjective magnitude*, i.e. the amplitude of the vibration oscillation (analogue to the loudness of an audio signal); *frequency*, i.e. the period length of the oscillation (similar to the pitch of a musical tone); *temporal patterns*, i.e. the length of an individual stimulus or rhythm patterns composed of a number of stimuli; and *location*, i.e. the location on the body where the stimulus occurs. Van Erp reviews findings neurophysiological and psychological to derive a set of guidelines for how to encode information in these four parameters and highlights potential pitfalls and interaction effects.

MacLean and Enriquez [ME03] introduce haptic icons, i.e. *brief programmed forces applied to a user through a haptic interface*. They present a haptic icon editor [EM03] that allows controlling the rotation of a "door knob". With the editor, users can design sequences that exactly define the rotation of the knob at a given point in time, which can be used to create rotational forces. By varying amplitudes, frequencies, and durations the editor allows creating different complex shapes. Investigating the perceptual design of haptic icons [ME03] with this tool they found that people are well capable of differentiating individual icons when one or several parameters are altered.

Brewster and Brown [BB04] suggested the framework of tactile icons (Tactons), i.e. structured, abstract messages conveying information through touch. They extend the list of parameters of van Erp by adding *waveform*, i.e. the shape of an oscillation, such as sine, triangle, or rectangle (corresponding to the timbre of a sound); and they split timing into *duration*, i.e. the time between the onset of the offset of a single stimulus; and *rhythm*, i.e. groups of pulses forming complex patterns. Investigating the effectiveness of Tactons, Brown and Brewster [BBP05] found that users can recognise individual changes of these parameters effectively. Tactons encoding three types and three priorities of a notification in rhythm (representing type) and waveform (representing priority) had a recognition rate of 71%.

These studies suggest that encoding multiple information dimensions, such as the direction and the distance of a location, in the parameters of a tactile stimulus is feasible. However, each of the parameters has its own limitations and capabilities. Therefore, we will review fundamental findings on cutaneous perception in the following.



## 2.2.2 Cutaneous Perception Implications

However, each of these parameters has its own characteristics. Thus, in this section we elaborate the six parameters proposed by Brewster and Brown [BB04] and review research about their relevant capabilities and limitations. The important question this section aims to answer is, how much information can be encoded in each parameter, and which parameters might be suited or unsuited to encode the different dimensions of spatial information.

### 2.2.2.1 Amplitude

Amplitude refers to the magnitude of the oscillation. As shown in Figure 2.2 its maximum peak can be increased or lowered.

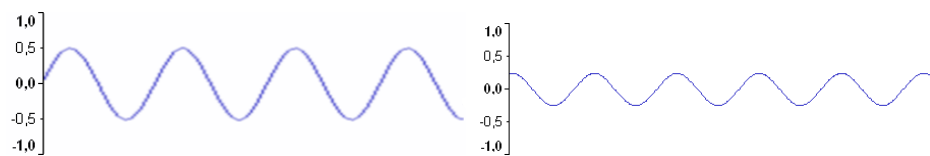


Abbildung 2.2: Amplitude: altering the magnitude of the stimulus oscillation.

The amplitude of a vibration stimulus maps non-linearly to the subjective magnitude of the vibration [vE02]. Amplitude can thus for example be described in dB, where 0 dB denotes the perception threshold. Pain occurs beyond 55 dB [GDO02]. However, since the perception deteriorates above 28 dB [She85] the usable range of amplitude is much lower. The most sensitive region for detecting skin indentation is the fingertip, being able to detect indentations on the region of 10 microns [KWyRT91]. The detection threshold also depends on the vibration frequency, being lowest around 250 Hz. The discrimination capability is largely independent from the stimulus location on the body. As just noticeable difference (JND), i.e. the minimum difference in the stimulus that can reliably be discriminated, values between 0.4 dB and 3.2 dB have been reported [GDO02]. Other sources say that amplitudes have to differ by 20% for a reliable discrimination [CS82] and no more than four different amplitudes can be discriminated reliably.

### 2.2.2.2 Frequency

Frequency describes the speed of the oscillation (Fig: 2.4). The perceivable range is denoted differently 20-1000Hz [GDO02, BB04], 10 - 400Hz [Sum92]. The skin is most sensitive around 250 Hz. The ability to discriminate different frequencies is finer at lower frequencies. For frequencies below 250 Hz the discrimination threshold is less than 5 Hz (shown for the fingertip). For frequencies above 320 Hz the discrimination capacities are significantly degraded [Gof67].

Measuring the discrimination threshold for frequency is difficult, since there is an in-

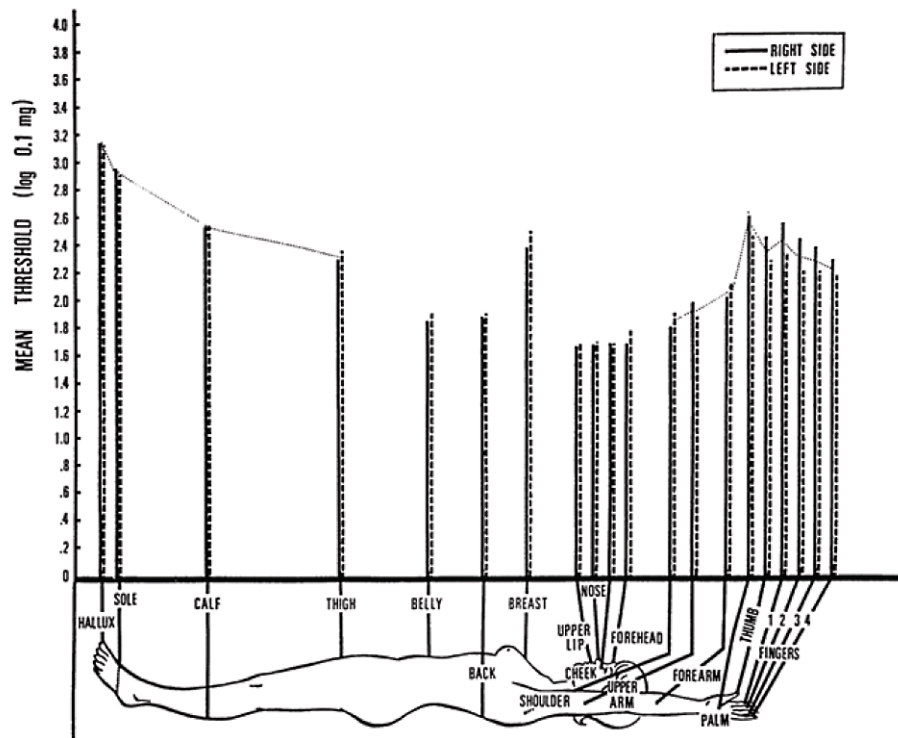


Abbildung 2.3: Sensivity Threshold Map (source: Weinstein1968)

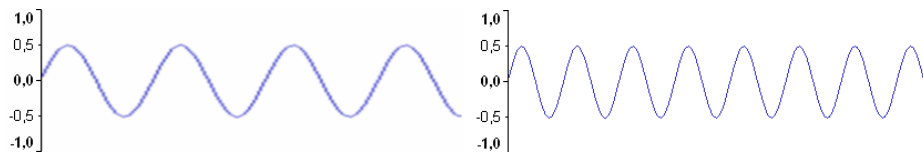


Abbildung 2.4: Frequency: the speed of the oscillation.

teraction between frequency and amplitude. For example, people perceive a change in pitch when the amplitude is altered although the frequency is fixed [Gel57]. Frequency also contributes to the perceived of a subjective magnitude [vE02]. Regarding the question how many different frequencies can be discriminated, the related work is inconclusive. [vE02] suggests not using more than 9 different frequencies. [She85] found that people could distinguish three to five different levels of frequency. Also comparing the frequencies of two different stimuli is much easier than absolute identification [BWE94]. Thus, when no reliable absolute identification is necessary but the ability to discriminate between two frequencies is more important, more frequencies can be used. Due to the interactions between amplitude and frequency several researchers have suggested that they be combined into a single parameter to simplify design [BB04]. Since both, amplitude and frequency, contribute to the subjective magnitude of a stimulus [vE02], the

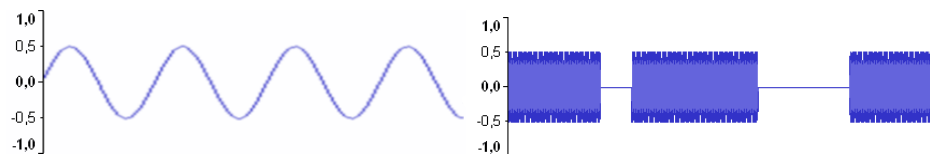
alteration of both parameters changes the perceived vibration intensity. [She85] found that this range could be increased to eight discriminable levels of subjective magnitude by adding amplitude to frequency as a redundant parameter.

### 2.2.2.3 Timing (Duration & Rhythm)

Timing can address the duration of a single vibration stimulus (see Fig. 2.5) or groups of pulses with different duration that compose tactile rhythm (see Fig. 2.6).



*Abbildung 2.5: Duration: alternating the lengths of the stimulus.*



*Abbildung 2.6: Rhythm: composing complex patterns from several stimuli.*

The temporal resolution of the skin is very high. It is capable of detecting gaps between stimuli down to 10 ms [vE02]. In comparison, the ear requires a delay of 30-40 ms to recognise a "pause". Short pulses (below 100ms) are perceived as taps or jabs [GDO02]. [She85] warns that too short pulses may result in undesirable sensations, such as pokes or jabs. The JND between the duration of two pulses is 50-150 ms for stimuli between 100 - 2000ms. Thus, in this interval at least 12 different pulse lengths should be identifiable. When the tactile signal is functioning as a simple alert, people prefer that the duration of the tactile pulses be between 50 and 200 ms, as stimuli of longer durations are perceived as annoying [KL05].

The human sense of touch is capable of interpreting complex temporal patterns, e.g. produced by speech [Sum00]. In a more systematic approach Brown and Brewster [BBP06] found that three different rhythms resulted into a recognition rate of 93% when those rhythms were presented in a 3-parameter Tacton together with different spatial location and waveform. Understanding different rhythm is however rather complemented by the human ability to make sense of the pattern than the perceptual capabilities of the skin.

### 2.2.2.4 Location on the body

Exciting different locations on the body can be used as another parameter where each location has a different meaning. The sensitivity and spatial acuity varies greatly at diffe-

rent body locations. Sensivity refers to the sensing threshold (minimum amplitude, see Figure X). The most sensitive and most accurate location is the fingertip [She85]. Discrimination threshold is below 1mm. Spatial acuity refers to the ability to discriminate two different stimulus locations (see Figure 2.7). If two stimuli occur too close together they cannot be discriminated anymore. Apparent location is the percept of a single stimulus induced by the simultaneous activation of two stimuli at different locations [25] van [vE02]. Since fingertip and hand are mostly used in everyday activities [CS82] many other placements of tactors have been investigated. Lindeman et al. [SMMPP05] name wrist [BGF<sup>+</sup>03], arm [TP97, CC03, BBP05, LS10], back [ELW<sup>+</sup>98, RB00], abdomen [Rup00, vEvV01, CBS04], and sole of the foot [KSTH98]. Only the head is discouraged for tactile information presentation as vibration can leak into the ear [GDO02].

Craig and Sherrick [CS82] report that rhythm pattern learned at one body location can almost immediately be recognised at other body locations. Optimal sensitivity is achieved at frequencies between 150 and 300 Hz for all sites, and at lower and higher frequencies the displacement of the skin must be greater to be detected [JS08]. When a spatial acuity of less than 4cm is sufficient, any location is suitable [Wei68, JP81]. However, different body locations allow for a much better acuity.

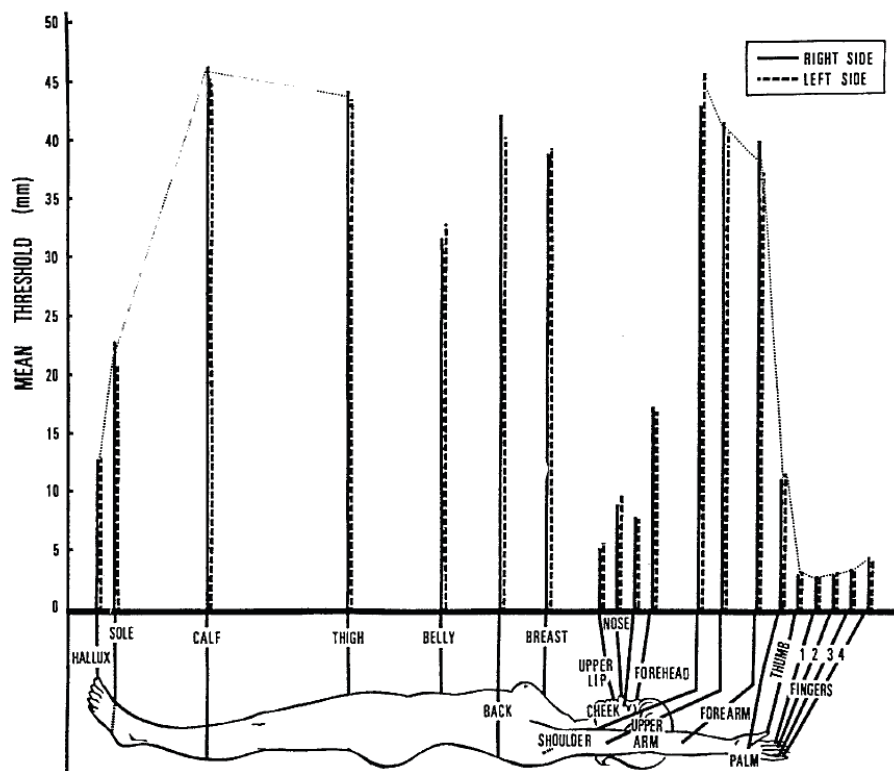


Abbildung 2.7: Two-Point Discrimination Threshold Map (source: Weinstein1968)

The perception on the arm has been investigated by Cholewiak et al. [CC03]. They found that stimuli occurring close to anatomic reference points are better localised than stimuli at other locations. Testing a 3x3 array of actuators on the forearm with 2,5cm spacing, Oakley et al. [OKLR06] found a recognition rate of 53%. Similarly, Lindeman and Yanagida [LY03] investigated the spatial acuity on the back. Placing a 3x3 array of actuators on the back with 6cm spacing resulted into a recognition rate of 84%. Cholewiak et al. [CBS04] investigated the spatial acuity on around the waist, comparing 12 actuators with 7,2cm spacing, 8 actuators with 10,7cm spacing, and 6 actuators with 14cm spacing. They found a localisation accuracy of 74%, 92%, and 97% respectively. They also confirmed the finding that localisation near anatomical reference points (navel and spine in this case) we more accurate.

### 2.2.2.5 Waveform

Like acoustic signals, vibration stimuli can have different waveforms, such as sine, saw, or even chaotic noise (see Fig. 2.8). In the area of acoustics these waveforms are responsible for the "timbre" of a signal. In contrast to the auditory system the human sense of touch seems to be rather insensitive to variations in the waveform [CBS04, SCW<sup>+</sup>97].

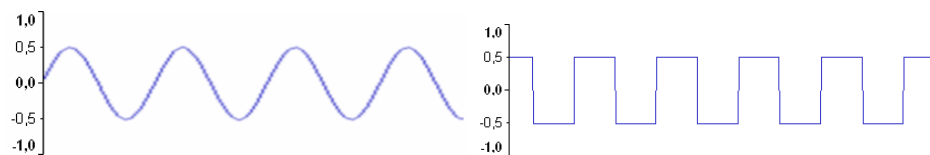


Abbildung 2.8: Waveform: shape of form of the oscillation.

Brown and Brewster [BBP05] could show that by modulating frequencies (e.g. 250Hz modulated by 20Hz, 30Hz, 40Hz) people perceive different levels of roughness on the forearm. The lower the modulation frequency the rougher the perception becomes. For three different waveforms they archived a recognition rate of 80%. In later studies of the same group [HB10] they were able to use four different levels of roughness presented to the fingertips by using a vibration motor and a piezoelectric actuator together. After 70 minutes of training, people reached recognition rate of 100%.

### 2.2.3 Actuators

Besides the limitations of the sense of touch there are also limitations arising from the available actuator technology. An actuator does not automatically allow to alter all six parameters of a vibration stimulus. Thus, this section reviews common types of actuators that can generate vibro-tactile stimuli.

### 2.2.3.1 Inertial Actuators

This type of actuators is based on an eccentric weight attached to a motor axis. When the axis starts rotating inertial forces are created which are perceived as vibration. This technique is cheap and robust and can therefore be found in many handheld devices, such as pagers of mobile phones. The disadvantage is that the created inertial forces occur within a plane, not along a single axis. This means the waveform of the vibration cannot be controlled. Further, frequency and amplitude are both dependent on the speed of the axis rotation and cannot be controlled independently. On the positive side, this actuator technology is widespread and it is easy to create considerable force with minimum effort.

### 2.2.3.2 Linear Actuators

Linear actuators, sometimes referred to as coil-based actuators, share their working principle with loudspeakers. A coil is moving up and down along one axis. If the coil is placed on the skin it can create a periodic indentation along a single axis. In theory this kind of actuator technology allows to independently control amplitude and frequency. However, most actuators require to be run at a resonance frequency, since otherwise the overall volume decreases significantly. On the good side, this actuator technology allows altering the waveform of the vibration signal.

### 2.2.3.3 Piezoelectric Actuators

These actuators exploit the piezoelectric effect. When electricity is applied to the (typically solid) material, e.g. ceramic, the material changes its form. By quickly changing the electricity level the material quickly expands and contracts and thus, when placed on the skin, created a periodic indentation, which is perceived as vibration. They share the characteristics with linear actuators but are far more expensive at the time of writing.

### 2.2.3.4 Electro-tactile Actuators

Electro-tactile actuators directly apply current to the human skin. The thereby created electric field direction excites the nerve fibers that would otherwise sense mechanical touch and vibration sensations. Electro-tactile actuators have the problem that the intensity of the perceived stimulus largely depends on the skin conductivity. This, however, may change dramatically, e.g. when the user starts sweating. Thus, the stimulus intensity is hard to control and may even result into pain.

### 2.2.3.5 Electro-static Actuators

A very novel form of vibro-tactile stimulation is being achieved by Senseg's electrostatic actuators<sup>1</sup>. Current is passed into and insulated electrode which creates a small attraction

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<sup>1</sup> <http://senseg.com/technology/senseg-technology>

to the skin through the Coulomb force. This technology allows created tactile pixels (tixels) which may ultimately lead to surfaces, such as handheld touch screens, which can create different forms of pressure or vibration. However, this technology is not yet widely available and primarily aims at very sensitive areas, such as the fingertips or the palm.

## 2.2.4 Summary

In this section the properties of parameters of vibro-tactile stimuli, namely amplitude, frequency, timing, body location, and waveform, we discussed. Regarding the task of conveying different levels of spatial information in different dimensions (distance and duration), not all of them are suited. Figure 2.9 summarises the capabilities of the six parameters.

Frequency		
Amplitude	—	About <b>8 levels of intensity</b> identifiable [She85]
Waveform	—	Hardly more than <b>2-3 levels</b> useful [BBP06]
Duration	—	About <b>12 levels</b> identifiable [She85]
Rhythm	—	<b>Highly capable</b> (think music) [Sum00]
Body Location	—	Safe distance 4cm [Wei68]

Abbildung 2.9: Summary of Tacton parameters and their ability to encode information.

Previous work has shown how to create up to four different discriminable *waveforms* on the fingertip. However, it is not yet clear if they could be discriminated when they are created on other parts of the body, such as the torso, as well. Further, four different levels might not be enough to satisfy all types of scenarios. With four and three to five discriminable levels *amplitude* and *frequency*, too, might fail to satisfy all types of scenarios. However, the interaction between both parameters and their perception as subjective magnitude, resulting into up to nine different discriminable levels, makes the combined parameter of *intensity* more powerful. Both timing parameters, *duration* and *rhythm*, lend themselves for the proposed context, since both allow to discriminate a large number of different levels. This is presumably only limited by the desired maximum stimulus length for duration, and the ability of the user to remember the meanings of individual patterns for rhythm. *Body location* is the most promising parameter as the body offers plenty of sites with a sufficient resolution. In addition, body location allows exploiting the spatiality of the body allowing for an intuitive mapping of stimuli to spatial information.

For designing Tactons, the most important aspect of the actuators is whether they have inertial or linear characteristics. Linear actuators have the advantage that they offer more control over altering parameters of the stimulus. This allows more flexibility and control when creating Tactons. However, linear actuators have two disadvantages: first, the additional control applies to the parameters of waveform, frequency and amplitude, which resemble the least powerful parameters. Second, linear actuators are rarely found in common devices, such as mobile phones. Thus, designing for linear actuators would mean to design for a very uncommon subset of tactile displays only. Inertial actuators, in contrast, are virtually ubiquitous. Every mobile phone is equipped with an inertial actuator. Their drawback is that they do neither allow to alter the waveform of a stimulus, nor control amplitude and frequency independently from each other. But, amplitude and frequency are altered proportionally, so increasing the rotation speed of the motor will increase the frequency and the amplitude of the created stimulus at the same time. This allows taking advantage of the better discriminability of the combined intensity of both parameters.

On the bottom line, body location, duration, rhythm, and intensity are the four parameters that seem to be suited for the given challenge of displaying spatial information. The can be created with the widely-used inertial actuators. Inertial actuators, although offering less control over the parameters of the vibration stimulus, may still be the better choice for designing Tactons when many levels of information need to be encoded in one parameter.

## **2.3 Related Approaches on Presenting Spatial Information with Tactile Displays**

From our revision of the fundamentals on how spatial information is organised in the human brain in Section 2.1 we argued that in the context of location-based services the location of a spatial entity is best presented by its direction and distance in relation to the user.

In the following we review related approaches of encoding spatial direction and distance with tactile user interfaces.

### **2.3.1 Encoding Direction**

How to encode directional information in vibro-tactile feedback has been investigated for more than a decade. One of the predominant approaches is to encode directional information in the location of vibro-tactile stimuli.



### 2.3.1.1 Tactile Arrays

In 1997 Tan and Pentland [TP97] proposed exploiting the Sensory Saltation effect [Gel75]. The Sensory Saltation effect, also referred to as the Cutaneous Rabbit, describes the illusion that a number of tactile stimuli created by a discrete number of actuators that are aligned in a row are perceived as a continuous movement (see Figure 2.10). Tan and Pentland used this illusion to fake the illusions of lines being drawn on the back. They proposed to convey spatial information, such as navigation instructions in these lines. For example, a perceived line starting at the lower left and ending at the upper right of the back might indicate to keep right.

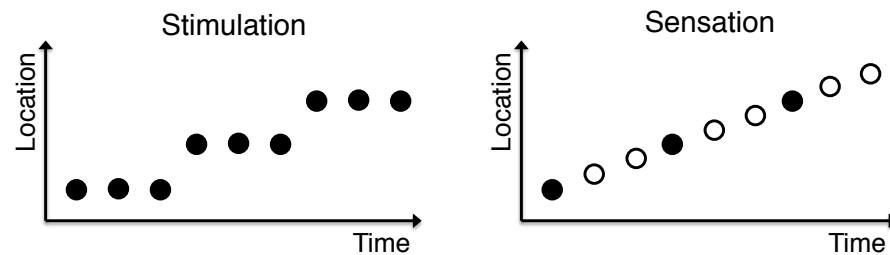


Abbildung 2.10: An illustration of the Sensory Saltation Effect [TP97]: the upper diagram illustrates the actual stimuli occurring at three different locations. The lower diagram shows the perceived locations of the stimuli. The open circles denote the perception of phantom locations that occur in-between two stimulus locations.

### 2.3.1.2 Tactile Vests

Another approach of conveying spatial information in tactile stimuli has been reported in [Rup00]. Rupert et al. investigated how to avoid spatial mishaps of pilots that may occur when flying with reduced sight by conveying the direction of gravity vector ("down"). They provided pilots with a vest that consisted of multiple actuators placed on a torso suit. When, for example, the plane rolled left the actuators on the lower left would activate. The further the plane rolls to the side the further the stimulus rises up. The results of testing the system on the co-pilot of a jet plane showed that it can prevent vertigo when the pilot performed acrobatic manoeuvres. Similar results have been found by van Erp et al. [vEGB06] who tested a similar interface with an astronaut on board of the International Space Station ISS, though this test was limited to a single participant due to resource constraints.

### 2.3.1.3 Tactile Belts

A similar approach geared towards pedestrians was proposed by Tsukada and Yasumura [TY04]. They proposed a tactile torso display called ActiveBelt to convey the direction of objects on the horizontal plane. Their prototype consists of eight vibro-tactile

actuators attached to a belt. When it is worn around the waist, the actuators get equally distributed around the torso. The vibro-tactile signals produced around the torso are intuitively interpreted as pointing directions. For example, when the front actuator is turned on it appears as the belt points forward.

Cholewiak et al. [CBS04] investigated how well people can localize different actuators of such tactile belts on the skin. They compared tactile belts with six, eight, and twelve actuators. In an experiment with twelve military students 97 %, 92 %, and 74 % of the stimuli could be correctly identified. Cholewiak et al found a significant decrease in performance between eight and twelve actuators. The results suggest that increasing the number of actuators will not necessarily lead to a more accurate display, since the human ability to locate stimuli around the waist is limited.

Van Erp [vE05a] investigated the exact characteristics of the mapping between a stimulus on the waist and the perceived pointing direction. In a lab study with ten participants they created a number of stimuli with a tactile belt comprising 15 actuators. The participants were asked to express the perceived pointing direction by placing a marker on a table surrounding them. The results showed that there is a systematic correlation between stimulus location and perceived pointing direction. As shown in Figure 2.11, they also suggest that there are two internal reference points, one for each body half. The perceived pointing direction of a stimulus can therefore be predicted by drawing an imaginary ray from a reference point through the body location where the stimulus occurs.

Applying a tactile belt as navigation aid has been investigated by van Veen et al. [vVSVE04, vEvVJD05]. They used a tactile belt for waypoint navigation. The belt indicated the direction of the next waypoint to reach. In a field experiment investigating this concept all participants were able to navigate effectively and efficiently.

Beyond pedestrians, tactile belts and vests have also successfully been employed to provide directional cues to vehicle operators, such as car drivers [vEvV01, AHB10, AB10, BAH11] or helicopter pilots [Rup00, vEvVJD05, vEGB06].

#### 2.3.1.4 Encoding Multiple Entities

How to encode the location of multiple objects has been investigated by Lindeman et al. [SMMPP05]. A vibrotactile stimulus at a torso site indicated the presence of one or more hazardous spots in the respective direction. In a virtual environment participants had to clear a building, as it would be the task of a soldier. The rule was to avoid exposure to any place that had not yet been cleared = seen by the participant. The tactile belt was used to indicate the direction of all places that the user was exposed to but that had not yet been cleared. An actuator was turned on if it pointed at an uncleared spot. These tactile cues had significant positive effects on the participants' performance. A similar approach was suggested by [FER<sup>+</sup>08]. Their goal was to present obstacles around the user. The direction of an obstacle was indicated by activating the actuator pointing into

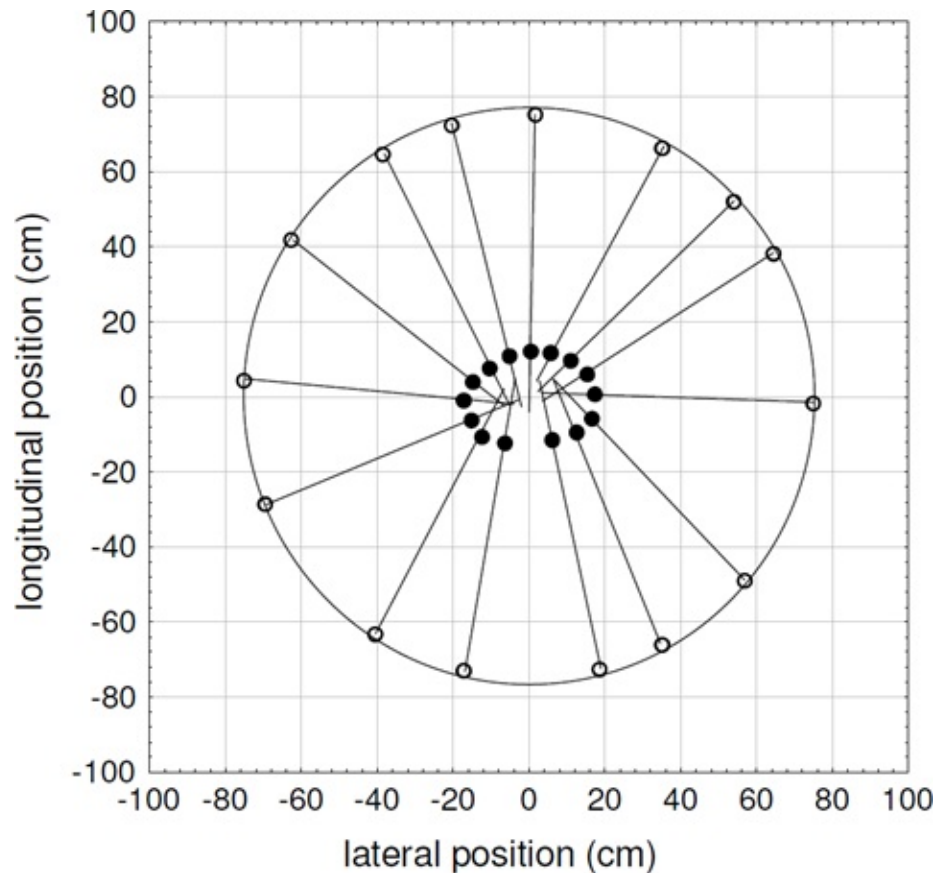


Abbildung 2.11: Results of the study on direction perception by [vE05a]: instead of the body midaxis as internal reference point, the results suggest the existence of an internal reference point for each body half.

its direction. However, the paper does not report from user tests. Since the presentation was simultaneous, the direction was conveyed fast, but there was no means of conveying additional information, such as the number of spots and their distance.

### 2.3.1.5 Single Actuators

Above studies show that tactile torso displays, such as tactile belts, are feasible and intuitive means of conveying directions with respect to the wearer's egocentre. Disadvantages of these early devices are that they are custom-made hardware devices, which might not always be available when the user is travelling. User might also just not want to carry such a device if navigation support is not required too often. Therefore, researchers have investigated whether navigation support can also be provided with the most ubiquitous tactile display: the vibration alarm of mobile phones. There are two predominant solutions, which Frohlich et al [FOBN11] refer to as the *magic wand* and *sixth sense*.

### Magic Wand Metaphor

The *magic wand* metaphor, as illustrated in the left of Figure 2.3.1.5, follows the idea that a user points at a distant object with a handheld device to learn about its presence or access information about it. Technically this is possible as nowadays smartphones are equipped with a digital compass. Recent implementations provide feedback when the user roughly points into the correct direction of a relevant geographic location, such as the travel destination [MMRGS10, RJE<sup>+</sup>10, WRS<sup>+</sup>10]. Thus, by actively scanning the environment the user can stay aware of the general direction of her or his travel destination. It has been shown that this technique is very intuitive and allows users to effectively reach a given destination [MMRGS10, RJE<sup>+</sup>10, WRS<sup>+</sup>10]. However, the intuitiveness is traded with the drawback that the device has to be held in the hand and actively needs to be pointed at the object, which has been found undesirable by some users [RJE<sup>+</sup>10].

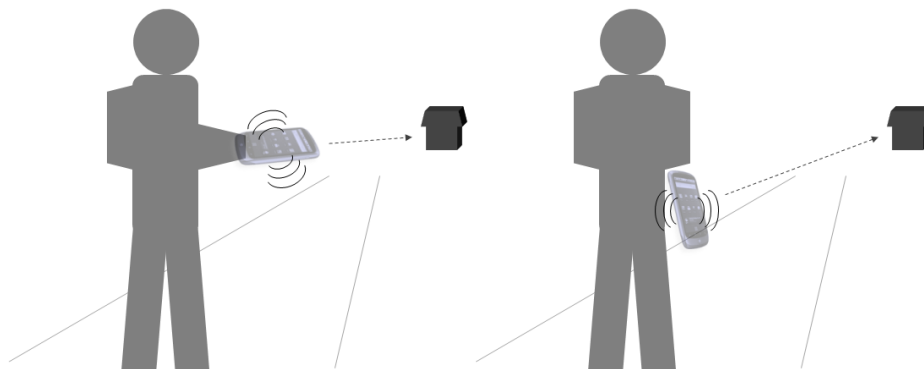


Abbildung 2.12: Magic Wand metaphor (left): user learns about location of an object by pointing at it with a mobile device; Sixth Sense metaphor (right): location of an object is encoded in the vibration itself.

### Sixth Sense Metaphor

The *sixth sense* metaphor, as illustrated in the right of Figure 2.3.1.5, describes solutions that use multimodal feedback to alert the user about changes in the environment. One approach following this metaphor was proposed by Lin et al. [LCY08]. They investigated encoding turning instructions into rhythm patterns. A pilot study with six participants showed that this forms an effective pedestrian navigation aid.

## 2.3.2 Encoding Distance

Van Veen and van Erp [vVSVE04, vE05b] investigated using rhythm patterns to encode the distance to the next waypoint in a navigation task. They used a tactile belt, which indicated the direction of the next waypoint by vibrating in that direction. They tested two approaches of altering the rhythm of the vibration to encode the distance to the next

waypoint. The first approach was a three-phase model where the rhythm pattern would change depending on whether the user had just reached a waypoint and needed to home on the next waypoint (phase 1), is travelling (phase 2), or is about to reach the next waypoint (phase 3). The second approach altered the pause length depending on the distance to the next waypoint. The closer the user gets to the next waypoint the shorter the pause becomes. In a field experiment comparing these approaches with a control condition participants completed all routes without problems. However, the distance encoding had no significant effect on the dependent variable, namely the effective walking speed. In fact participants walked fastest when no distance cue was presented, although the effect was not statistically significant. Our interpretation of these results is that people could walk their preferred walking speed in all conditions. Knowing the distance to the next waypoint will not make people walk faster. Altogether, the reported results do not allow to judge whether people could interpret the distance cues.

McDaniel et al. [MKCP09, MVK<sup>+</sup>10] investigated encoding spatial distance in the length of vibration stimuli. The goal was to allow blind people to understand where people in their proximity are located. Similar to the monotonic encoding by van Veen and van Erp they mapped the length of a pause between two stimuli to spatial distance. However, they did not alter the length of the pause continuously but they defined distance classes based on *proxemics*. According to Edward T. Hall [Hal63], proxemics is the study of socially meaningful distances between people as they interact. For example, when interacting with close friends and family these people may enter the personal space (be closer than 46 cm). However, if a stranger would come as close it usually feels inappropriate. McDaniel et al.'s design as described in [MKCP09] used these spaces to create a distance cue. The presence of a person is indicated by two short pulses of 50ms. Depending on the social distance (intimate, personal, social, public) the pause between these two pulses was altered (100ms, 250ms, 500ms, 1200ms). In a study with 15 participants (4 female) they investigated how well people can recognise these four distance classes. For the outer classes the recognition rate was above 90%. The inner two distance classes were mixed up more often, hence the recognition rate was between 85% and 90%. Including the recognition rate of the pointing direction 87% of all encoded locations were identified correctly. These results suggest that cueing locations through direction and distance is a feasible approach.

[FER<sup>+</sup>08] also describe a distance encoding based on the stimulus intensity. They reduce the vibration intensity the further the object is away. They also propose the notion of distance classes, namely close, near, and far. Nevertheless, since no user study is reported there is no evidence how well this approach works and how it is perceived by users.

## Summary and Conclusions

In Section 2.1 we have learnt that space is relational and, hence, the spatial location of any entity always needs to be given in relation to a frame of reference. We argued that the location of a spatial entity is easiest to interpret if the information is presented egocentrically, i.e. with respect to the recipient's body used as frame of reference. This can best be done by expressing its direction and the distance with respect to the body's location and heading (e.g. 2 o'clock, 100m). Entities that humans predominantly use to organise spatial information in the brain are landmarks. Thus, the goal this thesis will pursue is to present direction and distance of landmarks via the skin.

Section 2.2 has reviewed how information can fundamentally be presented via the skin. Since this thesis focuses on vibro-tactile information presentation we have reviewed the implications of the human's cutaneous perception, i.e. the part of haptics that comprises applying stimuli to the skin. Based on the framework of Tactons we have reviewed the capabilities of all six parameters that can be altered in stimuli to the skin. We found that a sufficient amount of information can be encoded in the intensity of the stimulus (combined alteration of frequency and amplitude), its duration, different rhythms, and its location on the body. Reviewing available actuator technology we argued that actuators with eccentric weights are the cheapest and most robust way of altering all of these parameters.

Section 2.3 we have reviewed previous approaches of presenting spatial information with tactile displays. We found that a common approach of presenting directional information is to use displays with multiple actuators that allow encoding directions through stimulation different body locations. The most promising approach are tactile belts that create stimuli around the belt, which are intuitively interpreted as pointing directions (such as 2 o'clock). For encoding spatial distance we found several naive approaches using all of the three remaining Tacton parameters (rhythm, duration, intensity). However, there are a number of things missing. It is yet unclear if these parameters can actually effectively encode distance and which one is best. Also, it is not clear how to encode direction and distance of more than one entity. Finally, it is not clear if spatial direction can only be encoded in body location or if other parameters are also suitable. This question is in particular interesting, since the ubiquitous smartphones have single tactile actuators.



### 3 Encoding Spatial Information in Spatial Tactons

In order to study whether location-based services that use tactile user interfaces can overcome the challenges of distraction, efficiency, and perception, we first need to be clear how the spatial information is to be delivered. As concluded from Section 2 this requires encoding the direction and distance of a spatial entity from the perspective of the user. Previous work has shown that cueing directions in the body location of a vibrotactile stimulus via tactile belts is a very effective and intuitive approach.

Our review of the related work concluded that three things are currently missing:

1. It is not clear how to encode the location of multiple spatial entities, so that each spatial entity is perceived. So far, previous work has only proposed to present the location of multiple entities by turning on all actuators that point in the direction of at least one spatial entity. This approach, however, will neither allow the user to be sure about the exact number of spatial entities nor will it allow to encode further information about each entity.
2. For cueing spatial distance different parameters have been proposed to encode spatial distance, namely rhythm, duration, and intensity of a vibration stimulus. However, only the parameter of duration has been subject to a test [MKCP09], where the participants recognised four different distances with an accuracy of around 90 %. The other two parameters (rhythm, intensity) have not been studied in that detail.
3. Much of the previous work focusses on the intuitive tactile belt display. However, the currently most widespread tactile display, the vibration motor in smartphones, is not addressed by this research. It is not clear whether the advantages found in previous work are due to the intuitiveness of the tactile belt or the sensory modality.

This chapter fills these gaps by presenting two new concepts of encoding spatial information. Section 3.1 proposes the novel concept of presenting the location of multiple spatial entities in serial order. In a lab study these concepts are evaluated and the three parameters for encoding spatial distance (rhythm, duration, intensity) are compared experimentally. We conclude that presenting the location spatial entities in serial order is a viable approach and that all three parameters are suited for conveying spatial distance. Section 3.2 introduces the novel concept of a Tactile Compass. It encodes directions in rhythm patterns and distance in the pause between two patterns. While this interface is less intuitive than a tactile belt it allows us to extend the applicability of our work to smartphones, too.



### 3.1 Encoding Location with Multiple Actuators (Tactile Belts)

The material in this section originally appeared in Pielot, M.; Krull, O. & Boll, S. Where is my Team? Supporting Situation Awareness with Tactile Displays. *CHI '10: SIGCHI conference on Human factors in computing systems*, 2010

Location-based services may need to present the location of more than one spatial entity at the same time. For example, when using a friend finder, users might want to be aware of the locations of all friends at the same time in order to estimate the location of the main group versus individuals. To satisfy this need with Spatial Tactons, we need to understand how to encode the location of several spatial entities at the same time.

While encoding spatial directions has been addressed by a number of studies, little insights exist in how to encode spatial locations (direction and distance). While conveying a spatial direction might be sufficient for some scenarios (e.g. in a navigation scenario, where it is sufficient to tell the traveler in which direction to walk), other scenarios may require a distance cue as well. However, it is not yet clear, which is the most intuitive and effective way of encoding distances. Thus core contribution of this section is an experiment comparing different designs of encoding the direction and distance of several objects via tactile belts. Using the Tactons framework we will argue that useful parameters for encoding distances are rhythm, duration, and intensity. The results of the study provide evidence that all of the three parameters are feasible, but that rhythm is a bit more accurate than duration and intensity.

#### 3.1.1 Encoding Multiple Directions

The approach reported in previous work [SMMPP05, FER<sup>+</sup>08] to encode the location of multiple entities is to activate all tactile actuators that point at at least one entity. However, this approach suffers from masking effects. If as for example shown in Figure 3.1 two of the three objects to display are located in the same direction. In a naive design this would mean that only two actuators vibrate. Hence, the user never knows if a vibration indicates the presence of a single or several objects in the given direction. On the good side this serves as a filter and keeps the amount of information to interpret low. On the bad side users might lose important information. One approach to this problem would be to encode whether masking occurs or not. This allows the user to discriminate between a single and multiple objects in the same direction, which can be sufficient if the situation of masking does not occur often. Another approach would be to encode the number of objects in a given direction. However, this would require using another Tacton parameter to encode the number of objects. Still, both approaches have the problem that with an increasing number of objects in one direction, it becomes increasingly complex to encode additional information about it, such as its distance.

As part of this thesis we investigate a different approach, namely conveying the lo-

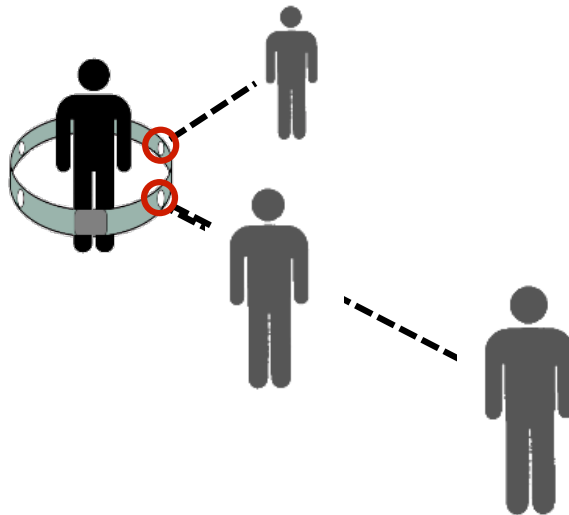


Abbildung 3.1: The drawback of simultaneous location encoding: objects can mask each other.

cation of objects in a sequential order. An example of this approach is shown in Figure 3.2. Instead of indicating the presence of objects in a sector, the direction of each object is being presented successively. For example in Figure 3.2, first the person to the left would be displayed, second the person right/ahead, and third the person right/behind the wearer. As in the related work, the direction of each person is displayed by turning on the actuators pointing most accurately into the direction of that person.

To avoid masking effects, a short pause separates the presentation of two directions. If two people are standing in the same direction, the user feels two pulses for the same direction. By the number of pulses the users can infer how many objects there are in one direction.

The advantage of this approach is that since only one location is presented at a time no masking can occur. Further, the full remaining space of Tacton parameters remains available to encode information in the directional pulse. The disadvantage of the approach is that for each added location to display the method will take longer to display all locations and that the user will have to remember more information. We assume that with an increasing number of objects the usefulness of this method will degrade. However, it shares this approach with the simultaneous direction presentation by Lindeman et al. and Ferscha et al., since with an increasing number of locations maskings become more and more likely.

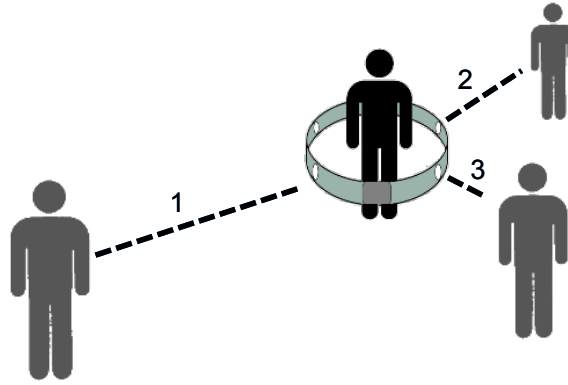


Abbildung 3.2: Novel approach we propose: convey the location of objects in a sequential order.

### 3.1.2 Encoding Spatial Distance with a Tactile Belt

As argued in Chapter 2.1.3 a location can be described by a direction and a distance cue. Thus, the question remains how to encode the distance of an object. In previous work different Tacton parameters, namely rhythm patterns, stimulus duration, and stimulus intensity have been proposed for encoding the distance between the belt wearer and the location to display.

#### 3.1.2.1 Related Approaches

All three approaches have in common that the mapping between stimulus parameters and distance is not intuitive in a sense that no explaining, no learning, and no mental processing would be required. All mappings have to be learnt by the user. However, typically a touch on the body means that the touching object has immediate contact to the body and thus has zero distance. Hence, it can be assumed that no intuitive mapping between a touch and spatial distance exists. All three groups provide credible justifications to encode the distance by the respective parameter (rhythm/duration/intensity). However, there is no systematic investigation yet on which Tacton parameters are suited for distance encoding.

#### 3.1.2.2 Distance classes

In order to effectively convey distances one has to understand how distances are represented in the mind. This can give useful insights on how to encode distances so they can be processed intuitively and with low effort. The notion of proxemics, as suggested by [MKCP09], gives a valuable hint that people internally actually do not calculate in terms of exact distances but classes of distances.

If one designs for a continuous perception of a perceived magnitude one has to take the psychophysical law (see e.g. [Ges97]) into account. It states that most physical stimuli do not map linearly to the subjective magnitude of the perceived intensity. Instead the perceived intensity grows logarithmically with linearly growing stimuli. A prominent example is the perceived volume of auditory stimuli, which grows linearly when the sound pressure doubles. This is not only true for stimuli of senses but also for mental size judgements. A famous example by Bernoulli, 1738 is the perceived value of money: a one dollar note added to two dollar notes is perceived as a much larger increase than adding the same dollar to 100 dollars.

We assume that similar rules apply to distance perception. If two people move one metre away from each other, it is a notable difference if they stand next to each other or if they are hundreds of metres apart. This is also supported by psychological research on proxemics, which investigates the distance that people keep when interacting with each other. According to Hall [Hal66] there are eight different distance classes (intimate space (close, far), personal space (close, far), social space (close, far), and public space (close far)) that matter in social interaction. For example, intimate space is within a radius of ca. 45cm around one person (presumably referring to Western cultures), and this space is reserved to family and closest friends. These classes could e.g. be applied when the goal is to convey proxemic information during social interaction. One noteworthy property, which might be transferable to other classifications of distance, is that the radiuses of proxemic spaces grow exponentially. On the bottom-line, most applications might want to convey distance classes instead of continuous distance values. Furthermore, the radiuses of the distance classes will usually grow exponentially. We assumed that people might find distance classes easier to process, while at the same time there is less information to encode for the tactile display. As a consequence, we assume that each application will define distance classes. The outer-most class defines the horizon beyond which locations are not displayed anymore. We refer to this horizon as the tactile horizon. The space within this tactile horizon is separated into a discrete number of distance classes.

### 3.1.2.3 Available Tacton Parameters

As laid out in Section 2.2.2 the parameters of a vibration stimulus that can be altered are amplitude, frequency, duration, waveform, rhythm, and body location. When asking which of these parameters are suited for encoding spatial distance, some can be excluded immediately.

As shown in previous work people can only discriminate 2-4 different levels of roughness when the waveform is altered. Altering the waveform required linear actuators, which are more expensive and usually required to keep the frequency fixed at the resonance frequency. We further have argued that frequency and amplitude both contribute to the subjective magnitude of the stimulus and are best used in combination. We referred to this as the vibration intensity. Finally, the body location of the stimulus is already in use

for encoding the direction of objects. Using body location to encode further information would require adding more tactons.

Hence, the most promising ways of encoding spatial distance are stimulus duration, stimulus intensity, and rhythm patterns.

### 3.1.2.4 Investigated Distance Encodings

In the following we will elaborate on how to encode spatial distance with by the above identified Tacton parameters duration, intensity, and rhythm. We will elaborate on three candidate designs, one for each parameter, which serve as subject of the subsequent user study.

#### Duration-based distance encoding (DUR)

For our duration-based distance encoding we draw on the design suggested by [MKCP09]. The duration of the vibration stimulus is increased with increasing spatial distance, as illustrated in Figure 3.3.

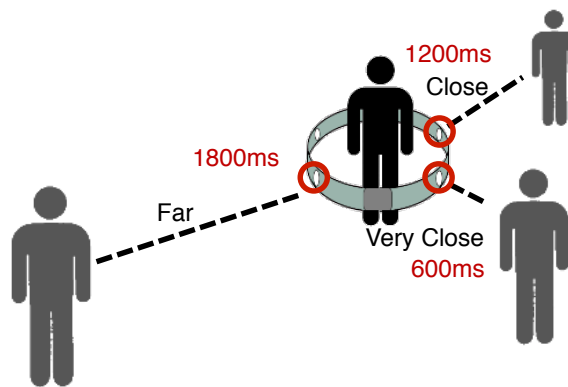


Abbildung 3.3: Duration-based distance encoding (DUR): the closer the object, the shorter it gets displayed.

The stimulus duration ranged from 0.6s from the closest distance to 2.4s for the furthest distance. Table 3.1 shows the stimulus durations used to encode each of the seven distance classes. For the mapping we applied the Weber-Fechner Law [Web46], so the stimulus duration increases exponentially with increasing distance. The rationale was to avoid the difficulties the participants to discriminate the middle distance classes reported by [MKCP09].

Distance class	1	2	3	4	5	6	7
Duration (s)	0.6	1.05	1.45	1.71	1.97	2.2	2.4

Tabelle 3.1: Mapping of distance classes to stimulus duration.

### Rhythm-based distance encoding (RHY)

For the rhythm-based design we followed the concept of the three-phase model by [vVSVE04], only that we assigned one vibration pattern to each of the seven distance classes. To make the mapping as simple as possible we numbered the distance classes from one to seven and assigned them series of vibration pulses with the same pulse count, as illustrated in Figure 3.4. For example, the third distance class would be represented by a series of three vibration pulses. Table 3.2 shows which number of vibration pulses maps to which distance class.

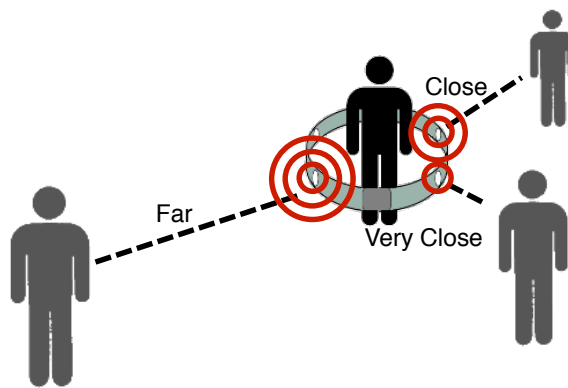


Abbildung 3.4: Rhythm-based distance encoding (RHY): the number of pulses indicate the distance class ranging from one pulse for the inner class to seven pulses for the outermost class.

Distance class	1	2	3	4	5	6	7
Pulse count	1	2	3	4	5	6	7

Tabelle 3.2: Mapping of distance classes to number of pulses.

### Intensity-based distance encoding (INT)

For the intensity-based distance encoding we used the design suggested by [FER<sup>+</sup>08]. We mapped increasing vibration intensity to decreasing spatial distance, as illustrated in Figure 3.5. This resembles everybody's experience from hearing, where the acoustic energy of a sound source gets weaker with distance, and hence its volume / intensity decreases.

The vibration intensity varies between 100% (closest class) and 9% (furthest class),

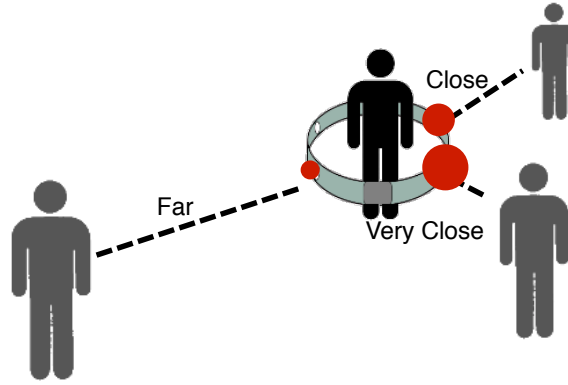


Abbildung 3.5: Intensity-based distance encoding (INT): the closer the object, the higher the intensity of the stimulus becomes.

where 0% refers to the detection threshold and 100% to the maximum vibration intensity of the used actuators. Again, we applied the Weber-Fechner Law, so the stimulus intensity increases exponentially with decreasing distance. Table 3.3 shows which intensity level maps to which distance class.

Distance class	1	2	3	4	5	6	7
Intensity (%)	100	78	60	45	32	20	9

Tabelle 3.3: Mapping of distance classes to stimulus intensity.

### 3.1.3 User Study

In order to evaluate above concepts we conducted a user study. The goal was to study:

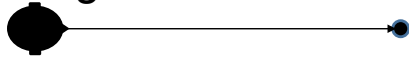
- **RQ 2.1:** how accurate do the different parameters allow to encode spatial locations?
- **RQ 2.2:** how intuitive are the different parameters?

Participants therefore were presented the location of spatial entities by a tactile belt. Using a graphical user interface they had to estimate these three locations. Using an experimental design we compared the three distance encodings (see Fig. 3.6) with respect to how accurate the participants could judge the locations and how intuitive they found the respective distance encoding.

#### 3.1.3.1 Material

As tactile display we used a tactile belt consisting of eight inertial actuators placed  $45^\circ$  apart.

## Encoding Distance



If *body location* is reserved for direction, three parameters remain

- **Rhythm:** encode distance in different patterns, e.g. increasing number of signals



- **Duration:** encode distance by increasing/decreasing length of signal

600ms

1200ms

1800ms

- **Intensity:** encode distance by increasing/decreasing intensity of signal



Abbildung 3.6: The three levels of the independent variable of this experiment.

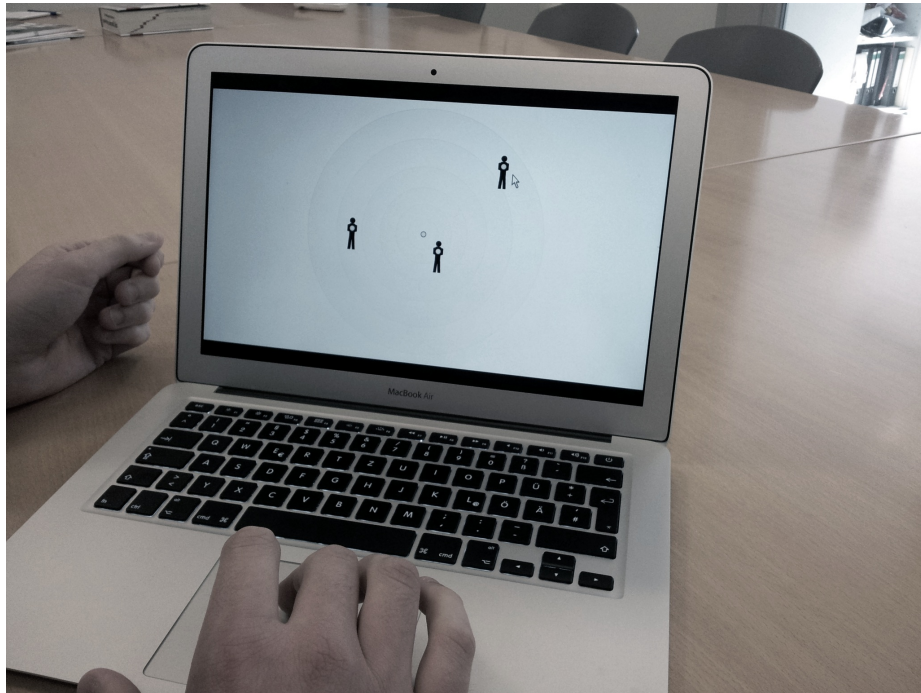
In order to let the participants express the spatial locations we provided test environment with a graphical user interface that allowed placing little icons to the perceived locations. Figure 3.7 shows a screenshot of the test environment. The circle in the centre represents the user's location. The top of the screen represents the forwards direction. The icons can be dragged to any location on the screen. The participants could then express a perceived location by dragging an icon to the respective location on the screen. The application hence allowed them to recreate the spatial information that was conveyed by the tactile belt.

In advance, 45 locations were generated randomly. Each location was described by a direction in relation to the user's heading (e.g.  $90^\circ$  means right of the user) and a spatial distance. The distances of the locations were given in pixels, since we then could directly use the pixel coordinates of the test environment's graphical user interface as reference. Additionally, we computed in which of the seven distance classes the location fell. For presenting the location with the belt, we mapped each direction to an actuators and a distance class. For example,  $38^\circ$  and  $150px$  would correspond to the front-right actuator and distance class 3.

### 3.1.3.2 Participants

Nine participants (two female) took part in the study. Their age ranged from 23 to 63 with an average age of 31.56 (SD 12.07).





*Abbildung 3.7: A participant trying to position the three figures to match the location perceived via the tactile belt.*

### 3.1.3.3 Design

The different methods of distance encoding (as described in subsection served as independent variable. The study used a repeated-measures design: all three encodings were evaluated with each participant. To cancel out sequence effects, the distance encodings were applied in random order. For each encoding we investigated the accuracy and the intuitiveness.

#### Accuracy

The accuracy was measured in terms of how exact the participants could judge the locations. We therefore obtained the direction error, the distance error, and the overall position error (see Fig. 3.8). The direction error  $\alpha$  was obtained by comparing the angle difference between the presented and the judged positions of each location. The distance error  $|a - b|$  was obtained by calculating the absolute pixel difference between the presented position's distance and the judged position's distance to the virtual user in the screen's centre. The position error ( $p$ ) was obtained by calculating the pixel distance between the presented and the judge position.

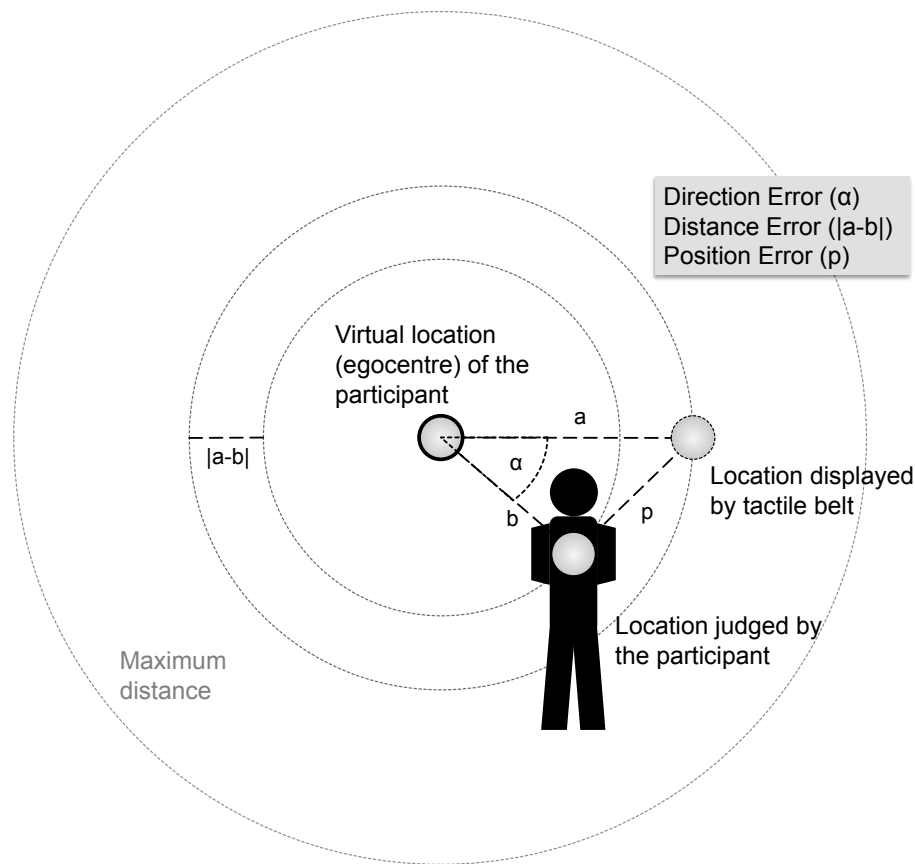


Abbildung 3.8: The accuracy related dependent measures: the direction error ( $\alpha$ ), the distance error  $|a - b|$ , and the position error ( $p$ ).

### Intuitiveness

The intuitiveness of the display methods was measured by response time and subjective self-reports. The participants were asked to rate the statements "*I found it easy to judge the distance of the objects.*" and "*I found it easy to judge the direction of the objects.*" The scale ranged from 1 (do not agree) to 5 (do fully agree).

#### 3.1.3.4 Procedure

In the beginning we created a custom user profile for each participant. For each actuator of the tactile belt we therefore assessed the stimulus detection threshold. In an iterative process, the participants were displayed as set of pulses with changing intensity closer to the suspected detection threshold. They then had to state the number pulses they had felt. The response was used to narrow down the intensity range until the detection threshold

was sufficiently approximated. This process was necessary to ensure that the intensity-based distance encoding worked fine for all participants.

Then, the participants were introduced to the three display methods in a live demonstration. We presented them different locations through the tactile belt and showed the correct location on the graphical user interface of the test environment. During that test phase, all three distance encodings were used. In addition to the direct experience, the participants could study visual illustrations of the methods (similar to the Figures 3.3, 3.4, and 3.5).

Once the participants felt confident enough the measurement phase began. The test environments presented three icons which had to be moved to the suspected locations by the participants. When the participants were content with their placements, they pressed the SPACE bar to get the next set of locations displayed. Between the changes of the distance encoding there were short breaks where the participants could recall the upcoming encoding's mode of operation and test it again.

In total, each participant judged the locations of 45 locations, 15 locations for each condition presented in five sets. Once all locations had been judge we asked the participants to express their thoughts and asked them to fill out the questionnaires containing above names statements.

### 3.1.4 Results

Table 3.4 shows the quantitative results of the experiment. Repeated-measures ANOVA and pairwise post-hoc Tukey comparisons were used to test for statistically significant differences.

<i>Measure/Condition</i>	<i>Duration</i>	<i>Rhythm</i>	<i>Intensity</i>
<b>Accuracy</b>			
Direction (deg)	19.2 (17.4)	21.9 (17.7)	20.6 (15.7)
Distance (px) ***	62.6 (42.6)	<b>34.5 (26.6)</b>	60.7 (46.0)
Position (px)	19.2 (17.4)	21.9 (17.7)	20.6 (15.7)
<b>Intuitiveness</b>			
Response Time (s) *	<b>25.4 (10.1)</b>	23.7 (8.51)	22.6 (10.2)
Judging Direction (subj) *	4.00 (.71)	<b>3.44 (.73)</b>	4.11 (.78)
Judging Distance (subj)	2.78 (.97)	3.56 (.88)	2.33 (.87)

*Tabelle 3.4: Results. Tables show means per condition. Values in parentheses are standard deviations. Asterisks indicate level of significance ( $p < .05$  \*,  $p < .01$  \*\*,  $p < .001$  \*\*\*). Bold values are different group according to Tukey post-hoc tests.*

The direction error  $\alpha$  was measured by averaging the unsigned difference between the correct and the judged azimuth from the virtual user to the centre of the icon's location.

The position error  $p$  was measured by averaging the distance between the correct and the judged position of the icon. No significant effects could be found on these two measures.

The distance error  $|a - b|$  was measured by averaging the absolute difference between the distances of the judged and the correct location of icon with respect to the virtual user. There was a significant effect on the user rating ( $F(2) = 3.40, p < .05$ ). The participants found it significantly easier to judge distances in the rhythm condition than duration ( $p < .001$ ) and intensity ( $p < .001$ ) conditions.

The response time was measured by averaging the time it took a participants finishing to reproduce one set of locations. There was a marginally significant effect  $F(2) = 3.02, p = .07$ . Participants responded significantly slower in the duration condition than in the rhythm ( $p < .05$ ) and the intensity ( $p < .001$ ) conditions.

There was also a significant effect on how difficult the participants found it to judge directions ( $F(2) = 3.40, p < .05$ ). The participants found it more difficult to judge directions in the rhythm conditions than in the duration ( $p < .05$ ) and the intensity ( $p < .001$ ) conditions.

#### 3.1.4.1 Comments and Observations

Regarding intensity three participants found it difficult to judge differences in the intensity levels. Some suggested reducing the number of intensity levels. One participant also proposed to inverse the intensity to distance mapping, so a far objects would be displayed with a greater intensity. Two participants also suggested making the pulses longer to make the direction judgement easier. Regarding duration four participants stated that the pulses were to long in general. They suggested reducing the overall duration. One participant mentioned the distance encoding confusing. Regarding rhythm two participants suggested to prolong the duration of each pulse so it would be easier to judge the displayed direction.

#### 3.1.5 Discussion

Altogether, the participants were able to infer the presented location with all designs. The serial presentation of directions posed no problems during the given task. The rhythm-based pulse count allowed the most accurate position judgement and was found most intuitive for judging distances. However, it was also found to be more difficult to judge directions. The duration-based distance encoding had the slowest response times, though the difference is only marginally significant.

We assume that rhythm allowed the most accurate judgment of distances since the participants were able to count the number of pulses to exactly know the specified distance class. Although the distance classes were not visible, this allowed the participants to give a better estimate about distance on the screen. On the negative side it could be

assumed that this strategy requires a more conscious processing of the cues. However, since the participants were not in a rush, this remains to be investigated.

Although the rhythm-based pulse count allowed the most accurate judgements, participants found it more difficult to accurately judge the direction of the displayed location. From the participants' comments it can be assumed that the shortness of the pulses could have caused this subjective impression. Some participants suggested making the pulses longer to make it easier to judge directions. This would however amplify the disadvantage, that for the classes further away, the information encoding gets longer and longer. It is also questionable how this method would behave, when increasing the number of distance classes. One limit might be the human ability to not remember more than 7 +/- 2 memory chunks at a time [Mil56]. More distance classes might make it necessary to pay attention to the pulses and count the number of pulses, which would significantly increase the workload.

The direction mapping between the distance and the continuously adjustable parameters duration and intensity worked fine. However, the used mapping based on the assumption that the Weber-Fechner Law [Web46] applied to the cognitive mapping of a tactile stimulus' intensity/duration to perceived distance. This assumption has not been validated and other mapping might result in a more accurate and intuitive distance perception. It is also questionable how much of the mapping can be done by intuition and how much has to be learned and trained.

Our work also assumes that seven distances classes are sufficient. This, however, strongly depends on the use case. Regarding intensity and duration it might even be possible to completely forgo distance classes completely and map metric distance to intensity and duration. User might still not be able to distinguish between e.g. 100cm and 101 cm but with regular training their distance perception acuity might increase significantly beyond what is possible with the rhythm-based pulse count.

The main limitation of these findings is the small sample size. With nine users, it is likely that existing effects have not been uncovered. For example, a two-condition, repeated-measures study with 9 participants reveals large effects (Cohen's  $d \geq .8$ ) with a likelihood of 55.9

### 3.1.6 Conclusions

The presented experiment provides evidence that the location of multiple spatial entities can be displayed with reasonable accuracy and intuitiveness by encoding each entity's direction and distance in serial order with a tactile belt.

In conclusion, all three tested parameters (rhythm, intensity, duration) allow encoding spatial distance, but none proves to be particularly intuitive. This is not surprising, as normally a touch sensation is caused by an object touching the skin. The rhythm-based design performed best in the objectively judged distance but this advantage might be

neglected if the user does not have the resource to count the pulses. The tested duration-based design caused participants to fulfil the given task slower.

Though these results should be seen preliminary, they favour the rhythm-based approach, as it objectively performed better in conveying spatial distance. Intensity could be used if the duration of the pulses should be kept short. Duration can be used as a fall back if e.g. rhythm is used otherwise and intensity cannot or shall not be altered.

### 3.2 Encoding Location with a Single Actuator (Tactile Compass)

The material in this section originally appeared in Pielot, M.; Poppinga, B.; Heuten, W.; Schang, J. & Boll, S. A Tactile Compass for Eyes-free Pedestrian Navigation *INTERACT 2011: 13th IFIP TC13 Conference on Human-Computer Interaction*, 2011

In this section we describe our design that explores how to convey geospatial locations with a single vibration motor and without required explicit interaction. To underpin our design decisions we first elaborate the requirements and constraints given by the pedestrian navigation task and the device limitations. We then describe how we investigated the design space to find a set of possible solutions and illustrate the prototypes we built. Afterwards, we present the results from a qualitative outdoor evaluation of the design prototypes. Drawing on our findings we illustrate the final design of our tactile compass.

#### 3.2.1 Investigation of the Design Space

The pointing-interaction proposed in previous work [MMRGS10, RJE<sup>+</sup>10, WRS<sup>+</sup>10] would already propose a viable solution to the above requirements. However, pointing means that the user has to interact explicitly with the mobile device to find the location of the destination. As reported in [RJE<sup>+</sup>10] users may desire constant tactile feedback but are not willing to constantly hold the device in the hand. Thus, the tactile compass should work hands-free. If no explicit interaction, such as pointing, shall be required the spatial information has to be encoded by the tactile stimulus only. While the visual and acoustic feedback can provide a huge variety of information, tactile information presentation is limited in multiple ways. On the one hand, humans can only perceive vibro-tactile stimuli if the actuator can stimulate the skin. On the other hand, the tactile feedback can only be varied in limited ways, depending on the used actuator technology. Most mobile phones only allow turning the electric motor on and off, which generates vibration through an off-centred weight attached to the motor axis. Theoretically, altering the voltage applied to these motors should allow to alter the subjective intensity. However, virtually none of the phone APIs allows to control this parameter, in particular this is impossible in iOS and Android, the two currently most predominant phone OSs. Thus, only vibrations with different length or rhythms can be created. Other parameters (see [BB04]), such as the frequency, the amplitude, or the waveform of the vibration cannot be altered.

In order to investigate how to cue the location of a place in relation to the user's location we conducted a focus group with five colleagues from our research group. We brainstormed potential solutions, identified common concepts, and derived five prototypes.

The most prominent aspect we identified was that every method we could think of either represented direction or distance information. Examples of this are describing locations by their distance and their azimuth with respect to a person using the clock face, such as "2 o'clock, 150 metres". All other approaches would require external means of geospatial referencing, such as landmarks or GPS coordinates. The other prominent aspect was whether the presentation was binary or if it had multiple levels. For example, being *near the destination* versus being *not near the destination* would be a binary distance representation. The distance to a destination in metres would be an n-ary presentation. While some of these combinations are reasonably suited to the problem, others are obviously insufficient to guide a pedestrian efficiently to a destination. Indicating in a binary way whether the user is at the destination or not would not be much help in reaching the waypoint in the first place.

### 3.2.2 Implementation of Prototype Methods

In summary we assumed that conveying absolute distances, distance changes over time, and general directions were the most promising ways of guiding a person to a place or destination. We used these elements of our design space to construct five different methods to guide people to a given geo location.

Technically, each method allows specifying a destination by a pair of latitude/longitude coordinates. Further, each method is fed with the GPS signal of the mobile phone, so it knows the user's geo-location, heading and walking speed. For each method, we had to design a mapping from the information that shall be presented to a set of rhythm patterns. Further, we already optimised the methods where it seemed suitable although that may have diluted the "pure" aspects.

#### Approaching/Departing

This method focuses on conveying the relative distance to the location as it changes over time. It indicates whether the user is walking towards presented location or not. User can reach the destination following the "walking towards the location" signal. Walking towards the waypoint is encoded in a single long (240 ms) pulse. Not walking towards the location is encoded by two short pulses of 120ms with a pause of 120ms between them. We defined "approaching" when the location is within a cone of  $2 \times 60^\circ$  in front of the user.

### Hot 'n' Cold

This method draws on the child game hot 'n' cold. It indicates the absolute distance to the location. By moving into the direction where the signal gets "hotter" the user will eventually reach the destination. Therefore the method continuously generates a single tactile pulse of 120ms. The distance between the user and the location to each is encoded in the pause between the pulses. The closer the user gets to the waypoint the shorter the pause becomes. The pause durations range from 5000 ms (1000 metres or beyond) to 300 ms (reached the destination).

### Left, Right, Ahead

This method encodes if the waypoint is left, right, or ahead of the user. The waypoint being left of the user is encoded in two pulses of 120ms. The waypoint being right of the user is encoded in three pulses of 120ms. To avoid having the user running zigzag we introduced a small frontal corridor, which indicates if the location is in a cone of 30° in front of the user. This case is encoded by a single 120ms pulse.

### Continuous Direction

This method encodes the exact direction of the location in the 360° full circle. It therefore creates a rhythm pattern that is altered continuously depending on the direction to present. If users are able to interpret the rhythm patterns they can just "read" the direction of the location and head into the respective way. The basic principle of the method is to encode the direction in the relative lengths of two vibration pulses. If the waypoint was dead ahead both pulses have a length of 80ms. If the location is right of the user, the length of the second pulse is increased. The further right the location gets the longer the second pulse becomes. Locations to the left of the user are displayed by increasing the length of the first pulse.

During our repeated early tries, we found that it was necessary to communicate when a waypoint is being reached and when the GPS signal is becoming too bad. Thus, each method implemented two basic Tactons: A short reoccurring pulse followed by a long pause indicates insufficient GPS signal quality. A sequence of three pulses (short, long, short) was used to announce that the destination has been reached: the first and the last pulse had a duration of 80 ms, while the middle pulse had a duration of 500 ms. The pause between those pulses was 120 ms.

#### 3.2.3 Qualitative Evaluation of Designs

We conducted a pilot study to figure out, which of the design approaches is most suited as a tactile compass for navigation. Therefore, the four methods were prototypically implemented on a Nokia N95. In addition, the prototype allowed us to define and store



geo locations. One then could select a geo location and choose a method to display its location.

## Method

The pilot study was conducted in a residential area near the OFFIS Institute for Information Technology in Oldenburg, Germany. The geo coordinates of four places were designated as destinations and stored in the prototype. Seven participants, who were partially familiar with the covered area, took part in the study. Each participant had to reach all destinations in the same order. For every destination another method was used. To avoid order effects the order of methods was randomised amongst the participants to avoid sequence effects. Beyond the tactile feedback the participants had no other cues about the location of the destination.

Qualitative data was collected through thinking aloud as well as video recording. All participants signed an informed consent prior to the study. At the end of the study the participants were asked to rank the design approaches and discuss their impressions about each of them.

## Results and Discussion

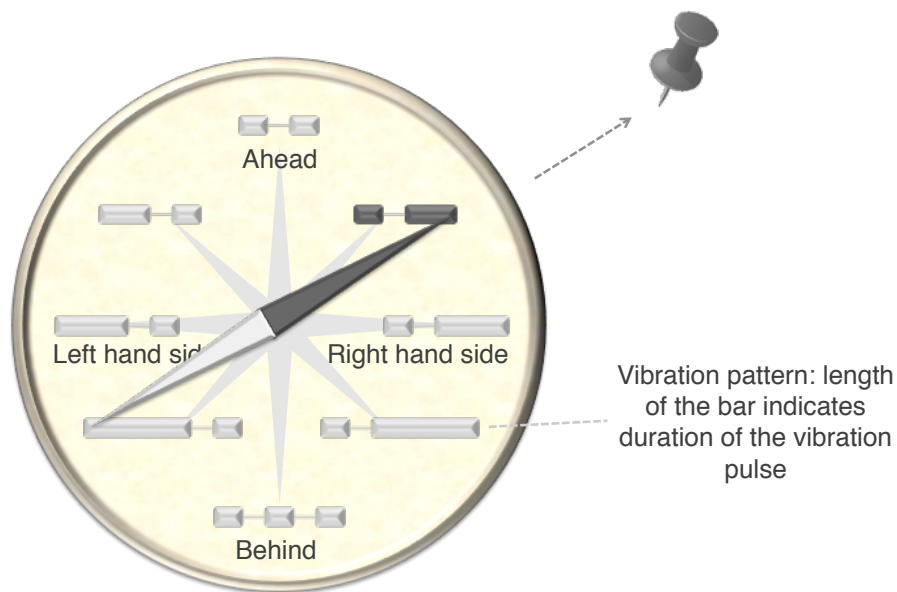
In all but four occasions the participants were able to reach the given destination. In general, all methods were found to be reasonably effective. The four breakdowns were instances of a participant standing on one side of a building while the destination was located on the other side.

Many participants did not like the distance-based methods since they required them to actively seek the destination. Direction-based methods were preferred over distance-based methods. Five informants named the Continuous Direction method as the most preferred one. Although it was found to be the most complex method, the informants appreciated its rich feedback. In particular, informants appreciated that they could observe how the direction of the destination slowly changes while they are moving.

In some cases obstacles such as larger buildings or blind alleys with the destination point behind them lead to confusion. In order to avoid the obstacles, the participants had to change their direction and accept the advice that their direction is wrong until they passed the obstacle. This caused irritations because the participants were not happy with foregoing the instructions of the system. It was stated that more waypoints on the route could help to resolve this issue.

However, there are a few limitations to the results. The methods we tested are only instances of the design space we laid out above. Neither the design space is necessarily complete nor might the instances have been the best examples for the entities of the design space. Nevertheless, the results suggest that participants prefer direction-based methods with rich information and are willing to accept complexity. Thus, one challenge

would be how to encode as much information as possible in the tactile cues, before they become too complex to be understood.



*Abbildung 3.9: The pointing direction is encoded in the relative length of two pulses. In this illustration the geographic reference point is somewhat to the right-hand side, so the first pulse remains short while the length of the second pulse is slightly increased.*

### 3.2.4 The Tactile Compass' Design

On the basis of the lessons learned from above pilot study, we designed a method based on the informant's preferred design, the Continuous Direction Method. As seen in Figure 3.9 we advanced the method by indicating locations behind the user in three short pulses. In addition, we added an absolute distance cue similar to the one we used in the Hot 'n' Cold Method. To encode the distance to the displayed spatial entity the pause between two pulse patterns is altered. The closer the user gets to the destination the shorter the pause becomes (see Figure 3.10). To improve the ability to discriminate the pulses we increase the length of the short pulses and the pauses between the single pulses of a pattern to 120ms.

To investigate the recognition rate of the Tactile Compass encoding we conducted a user study. The study was conducted as a preparation of the field study reported in Section 4.3.

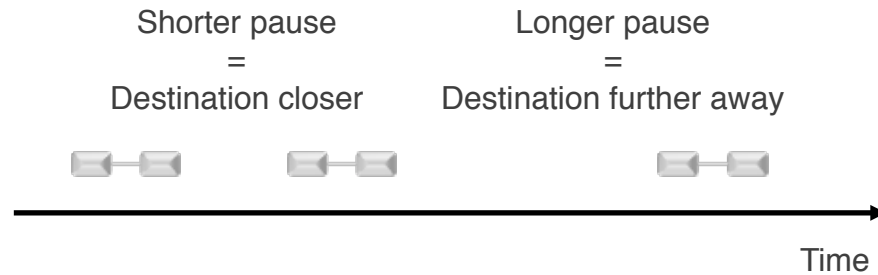


Abbildung 3.10: The distance is encoded in the pause between a set of pulses. The shorter the pause becomes the closer the user is to the presented location.

### 3.2.4.1 Methodology

Twenty-one participants (10 female, 11 male) took part in the study. Their age ranged from 18 to 41 with an average of 26.6 years (SD 6.68). None of these participants had been part of the previous pilot study, reported in Section 3.2.2, that informed the design of the Tactile Compass.

The study took place outdoors in the city centre of Oldenburg. The users sat down on a bench next to a sidewalk and a lively street and recognise angles presented by the Tactile Compass. Conducting the study outdoors had the advantage that this reflects the envisioned usage context of the Tactile Compass more closely than a quiet and calm lab environment. In particular, the traffic noise prevented participants from hearing the vibration motor.

The task was to recognise 16 random directions presented by the Tactile Compass. The participants could enter the judged direction through a compass rose showing on the screen. A little flag could be moved around and snapped to one of the eight directions the Tactile Compass could encode. The performance was quantified by measuring the response time and the correctness of the judged direction.

Before the participants actually started the task, we conducted a series of training sessions. First, we showed a visual representation of the Tactile Compass and the patterns associated with each of the eight direction (see Figure 3.9). The patterns could be played by touching the corresponding direction on the screen. Afterwards, the study was run in a training mode, where it did not store the performance. Instead, for each direction in provided feedback whether the participants' judgment was correct, and what direction had actually been presented. Once the participants achieved a recognition rate of 70 % in the training mode we started the actual study.

### 3.2.4.2 Results and Discussion

The participants recognised 78.19% (SD 14.61) of the presented patterns correctly. The mean response time was 7.56 (SD 2.17) seconds. Figure 3.11 shows the confusion matrix. The recognition rate for "ahead" and "behind" was perfect. All errors therefore occurred for "left", "right" and the four intermediate directions. Most of the errors represent a confusion of neighbouring directions, e.g. "ahead" was chosen instead of "front-right".

	estimated							
	Front	Front-Right	Right	Rear-Right	Rear	Rear-Left	Left	Front-Left
presented	Front		0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	Front-Right	25.7%		11.4%	2.9%	0.0%	0.0%	2.9%
	Right	0.0%	10.0%		16.7%	0.0%	0.0%	0.0%
	Rear-Right	0.0%	0.0%	7.7%		0.0%	0.0%	3.8%
	Rear	0.0%	0.0%	0.0%		0.0%	0.0%	0.0%
	Rear-Left	0.0%	0.0%	0.0%	0.0%		3.1%	0.0%
	Left	0.0%	0.0%	2.7%	0.0%	13.5%		10.8%
	Front-Left	0.0%	0.0%	0.0%	0.0%	5.6%	22.2%	

Abbildung 3.11: Confusion matrix. The numbers indicate the distance classes, where 0 = ahead, 1 = front-right, 2 = right, and so on. The dark red 25.7% has to be read that in 25.7% of all times where "front-right" was presented, it was mistaken for "ahead".

The results show that with some training participants are able to roughly judge directions from vibration patterns. However, the response time of 7.5 seconds also hints that this process is correlated with cognitive workload. The subsequent field study, reported in Section 4.3, confirmed both: the direction encoding was sufficient for effective navigation but we could observe an increased cognitive workload in the conditions with the Tactile Compass.

## Summary and Conclusions

In this chapter, we have addressed *RQ2: How can spatial information be encoded by tactile user interfaces?* We proposed Spatial Tactons, the concept of encoding spatial information for navigation and orientation in Tactons. Using the Tacton framework and analysing previous work on encoding spatial information in tactile displays we found that the most suitable parameters for encoding spatial information are the location on the body, intensity of the vibration, duration, and rhythm. Previous work clearly indicates the intuitiveness of mapping stimuli on the body to directions. Therefore, we focused on the challenges of how to encode multiple locations and how to encode spatial distances.

For encoding multiple locations we proposed to present the locations in serial order with a Tactile Belt as this allows to avoid spatial masking effects and to encode additional information, such as the spatial distance, for each location individually. For encoding spatial distance we found three approaches in the related work: using rhythm, duration, and intensity. However, these approaches had never been subject to a suitability analysis. We therefore conducted an experiment to compare the accuracy and the intuitiveness

of these three parameters for distance representation. The results show that all three parameters lend themselves for conveying spatial distances. Encoding distance in rhythm patterns allows the most accurate location judgment and was found most intuitive for judging distances. Intensity and duration were found to be more intuitive for judging directions. However, participants took longer to judge locations when spatial distance was encoded in duration.

Since Tactile Belts are rare kinds of displays we also investigated the feasibility of encoding spatial information with the vibration motor of handheld devices. This reduced the parameter space of potential Spatial Tactons to duration and rhythm. We tested four approaches encoding direction and distance in different ways and tested them with people in a field study. The most appreciated approach was also the most complex. It used rhythm patterns to encode different directions. By combining this approach with encoding the spatial distance in the duration of the pause between two patterns, we proposed the Tactile Compass. The Tactile Compass can encode the location of one spatial entity. It encodes eight different directions (ahead, left, right, behind, and the four intermediate directions) in eight different rhythm patterns. The spatial distance is encoded by increasing the pause between two patterns as the distance to the spatial entity increases.

The following three chapters will investigate, whether these Spatial Tactons allow addressing the three challenges of distraction, efficiency, and perception. Each challenge will be the focus of one chapter. The next chapter focuses on the challenge of distraction. We investigate if conveying navigation instructions via these Spatial Tactons can reduce the traveller's level of distraction compared to common handheld navigation systems.

## 4 Reducing Distraction in Turn-by-Turn Wayfinding

Having introduced Spatial Tactons to encode spatial information previous Chapter 3, this chapter focuses on the challenge of *distraction*. We investigate if Spatial Tactons can reduce the traveller’s distraction if they convey information that is crucial for the primary task. As scenario for this investigation we use the context of pedestrian navigation. This is done for three reasons: navigation requires to constantly consume spatial information, navigation often takes place in traffic where being distracted is a serious problem, and navigation systems are widely used instances of location-based services. We report from two field experiments that apply Spatial Tactons to provide navigation instructions by indicating the direction of the next waypoint. Our results provide evidence that Spatial Tactons can significantly reduce the traveller’s level of distraction when used to replace visual user interfaces existing in commercial navigation systems.

### 4.1 Background and Motivation

With more and more powerful handheld devices sold, location-based services and navigation systems have become common applications on our mobile phone. In particular, navigation aids, such as Google Maps, can be found on virtually any Smartphone (see Fig.4.1). These aids allow us to find our way in unfamiliar environments and places we never visited before. Typical applications locate users on a map and allow calculating routes. In addition, some recent navigation systems, such as Google Maps Navigation, also provide turn-by-turn instructions by text, visual cues, or speech.

Pedestrians, however, use these applications in different contexts than car drivers. For example, interacting with a handheld display on the move requires switching attention between the device and the environment, which results into fragmented attention [OTRK05]. Consequently, in a survey one in six adults reports to have physically bumped into another person because they were distracted using their phone [MR10]. Using speech and sound can help, but auditory user interfaces can be equally distracting. Authorities in Australia are speculating that the loss of situation awareness caused by listening to loud audio content via head phones might be a contributing factor to the still increasing pedestrian fatalities. Safety considerations aside; looking at a display or having to listen to spoken instructions might simply be undesirable, e.g. when having a lively discussion with a companion or if the user does not want to stand out.

As argued in Chapter 1.2 communicating information via the sense of touch will be less likely to interfere with our senses of vision and hearing. Conveying navigation information in Spatial Tactons might, thus, allow users to focus on the environment and provide [...] people a UI that’s less immersive, so that we can be more present for each

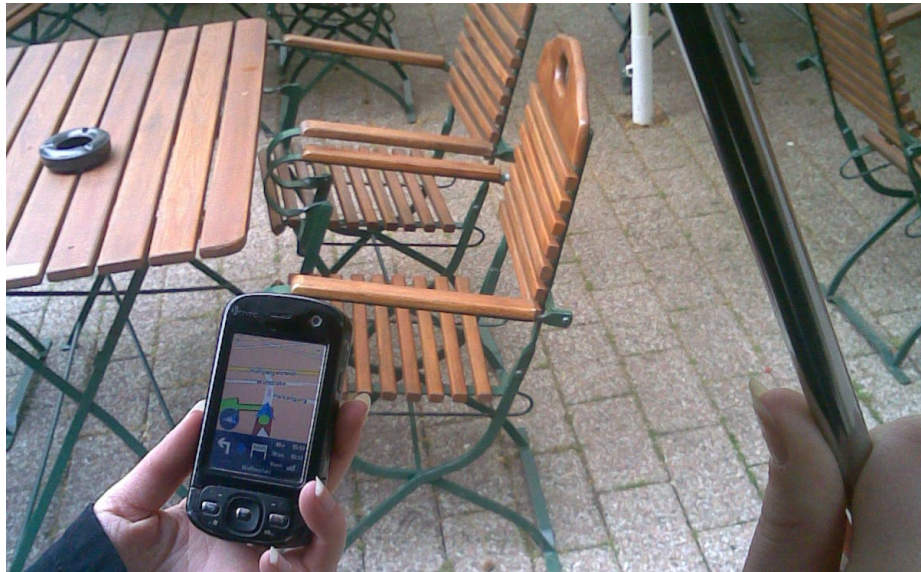


Abbildung 4.1: Using a handheld device for pedestrian navigation in an urban environment.

other, and more present for the environment that we're in right here.<sup>1</sup> However, it has yet to be shown that this can be achieved with tactile user interfaces and Spatial Tactons in particular. It is not yet clear if and how Spatial Tactons can be used in combination with today's pedestrian navigation systems. Shall they be used to replace or complement existing visualisations? Will they be beneficial in terms of navigation performance and distraction?

In order to study how Spatial Tactons can be incorporated into handheld pedestrian navigation systems and if they can reduce the level of distraction we conducted we conducted two field experiments. Spatial Tactons were used to complement and replace the user interfaces of common pedestrian navigation systems. Thirty-seven participants had to navigate through the city centre of Oldenburg, Germany with the Tactile Belt and the Tactile Compass. Reporting the results from these two experiments this chapter argues that Spatial Tactons can decrease the traveller's level of distraction significantly. Beyond that we found that the user's sense of direction was a major factor for the navigation performance.

<sup>1</sup> Marko Ahtisaari, Executive Vice President of Design, Nokia <http://www.guardian.co.uk/technology/2012/jan/31/ahtisaari-nokia-lumia-design>

## 4.2 Creating a Tactile Wayfinder with a Tactile Belt

The material in this section originally appeared in Pielot, M. & Boll, S. Tactile Wayfinder: Comparison of Tactile Waypoint Navigation with Commercial Pedestrian Navigation Systems. *The Eighth International Conference on Pervasive Computing*, 2010

This section reports from a field study comparing tactile waypoint navigation with Spatial Tactons to a commercial pedestrian navigation system with a classic visual user interface. While researchers have already proposed to use tactile belts as pedestrian navigation aids [TY04, vVSVE04, vEvVJD05, HBP08] the proof is still missing whether they will be beneficial in terms of distraction as well as navigation performance.

Our findings provide evidence that waypoint navigation with Spatial Tactons can free the users' attention at the expense of a decreased navigation performance. Further, we will show that the user's sense of direction strongly correlates with many aspects of the navigation performance and distraction. We will argue that Spatial Tactons are beneficial in terms of distraction but should rather be used to support the traveller's sense of direction.

### 4.2.1 Design of the Tactile Wayfinder

In this section we elaborate how we applied Spatial Tactons to provide turn-by-turn navigation instructions. The basic idea is to convey the location of the next waypoint along the route. Previous groups have shown that this concept can effectively be used for waypoint navigation. [vVSVE04, vEvVJD05, DEvER07, HBP08]. In this study we employed this concept in a prototype called Tactile Wayfinder.

Previously reported concepts of tactile waypoint navigation used a tactile belt to provide the location of the next waypoint. However, one of the drawbacks of pure turn-by-turn instructions is that they convey less spatial information than a traditional map-based navigation system. In particular, such traditional systems show at least a small part of a map which allows the user can use to learn how the route continues beyond the next waypoint. In previous concepts of waypoint navigation, however, the user would only learn how the route continues once she or he reached the next waypoint.

Therefore, we investigate using Spatial Tactons to give the user an idea how the route continues beyond the next waypoint. The Tactile Wayfinder, thus, does not only display the location of the next waypoint, but the location of the subsequent waypoint as well. The subsequent waypoint then serves as a *look-ahead*, giving the user a cue about how the route will continue once the next waypoint has been reached (see Fig. 4.2). However, to realise this concept, we had to refine the design presented in Section 3.1 so that the locations of the next waypoint and the look-ahead waypoint could be distinguished from each other by the user.



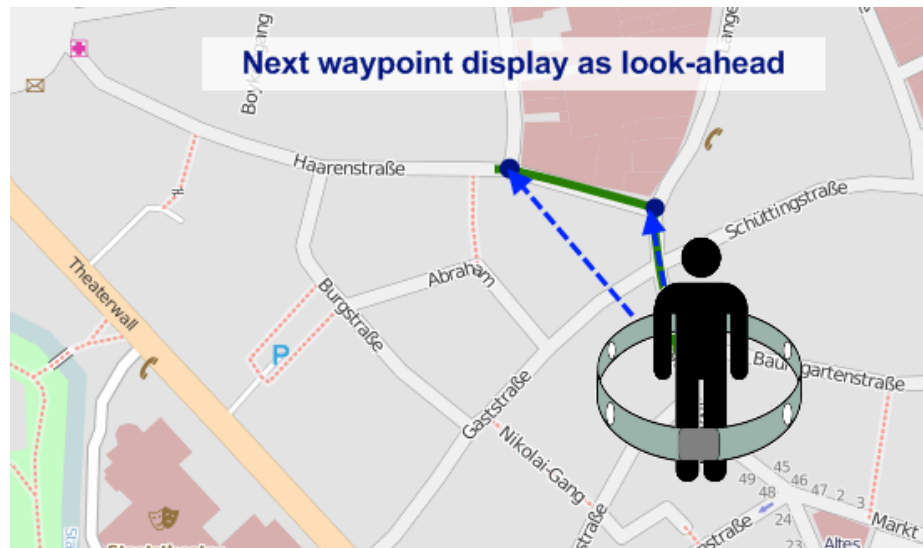


Abbildung 4.2: Route visualisation through a tactile look-ahead: in alternating order the current waypoint and the subsequent waypoint are displayed. The user can anticipate how the route will continue beyond the current waypoint.

#### 4.2.1.1 Tactons for Designing Tactile Cues

We therefore encode the type of the waypoint (next waypoint, look-ahead waypoint) in another Tacton parameter. In the case of the Tactile Wayfinder we created two two-dimensional Tactons where one information dimension encodes the direction of the waypoint and the other information dimension encodes the waypoint's type. We did not encode the waypoints' distances as previous work [vVSVE04, vEvVJD05] has found no effect of distance encoding on the navigation behaviour. The rationale behind this choice was to reduce the number of used Tacton parameters, so that the resulting encoding would be as simple as possible

As argued in Section 2.2.2 six different tactile parameters can be used to encode information dimensions: amplitude, frequency, duration, waveform, rhythm, and body location. These parameters can then be combined to compose multidimensional messages where each parameter is mapped to one information dimension, e.g. the body location encodes the direction and rhythm encodes the type. Tactons composed of two or three different parameters can be encoded with a fairly high recognition rate of 70%, 81% [BBP05, BBP06]. However, in these studies the parameter space was limited to three levels of body location and rhythm, and two levels of waveform.

Which parameters can be used for Tacton design depends on the tactile actuators. For our work, we used a tactile belt with 12 vibration motors using off-centred weights to generate vibrotactile stimulations (see Fig. 4.3). These actuators are sewn into flexible fabrics, distributing themselves equally around the torso when worn. In order to indicate

the location of a waypoint, the actuator which points most accurately into the waypoint's direction is activated. A built-in compass allows displaying absolute positions (e.g. North) independent from the user's orientation. Due to the off-centred weights the parameter space is limited. Changing the stimulus waveform is not possible with such actuators. Frequency and amplitude cannot be altered independently from each other, as they both depend on the applied voltage level, i.e. how fast the motor rotates. In this paper we refer to this combined parameter as *intensity*. This leaves us with four parameters for designing waypoint Tactons: intensity, duration, rhythm, and body location.



Abbildung 4.3: The tactile belt we used for the Tactile Wayfinder.

#### 4.2.1.2 Design of the Waypoint Tactons

As mapping body location to directions has shown to be intuitive and easy to understand [RB00, vE05a] we incurred this concept. We also kept the concept of presenting multiple spatial entities in serial order, as elaborated in Section 3.1.

For encoding the waypoint type (next or look-ahead) rhythm was used as parameter, since the study by Veen et al. [vVSVE04] showed that different rhythms can be distinguished well when walking. In a set of informal tests we tested several rhythm patterns outdoors to ensure that the patterns could be easily identified when walking. The rhythm pattern that were finally used to encode the waypoint type are illustrated in Figure 4.4. The next waypoint is encoded by a heartbeat-like pulse which is repeated five times. The look-ahead waypoint is presented with a single pulse. Both Tactons are repeatedly presented with a duration of approximately four seconds per cycle.

#### 4.2.1.3 Tactile Wayfinder Implementation

The tactile route visualisation with the waypoint look-ahead was integrated into the Tactile Wayfinder prototype. It was implemented using the open source Companion Platform<sup>2</sup> for rapid mobile application prototyping. As hardware platform we used a HTC Windows Mobile PDA. The belt was connected to the PDA via Bluetooth. A G-Rays

<sup>2</sup> <http://sourceforge.net/projects/companion-pf/>

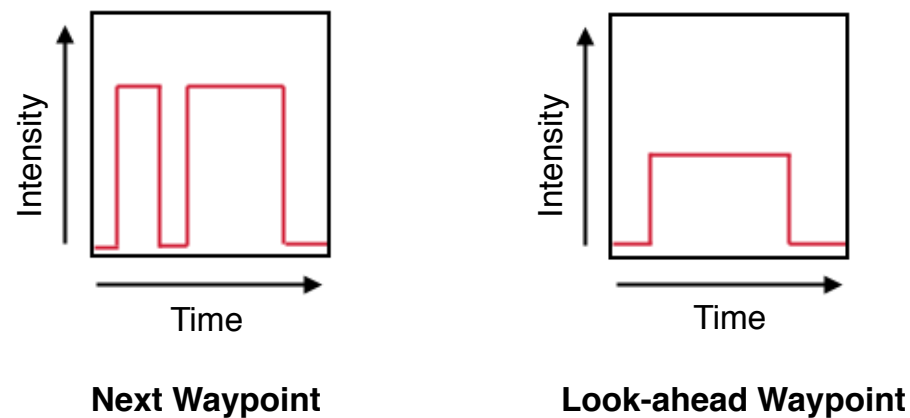


Abbildung 4.4: The used Tactons: the heartbeat-like pulse (left) indicated the direction of the next waypoint. A single pulse (right) is used for the look-ahead waypoint.

2 GPS receiver was used for obtaining the user's geo location. It was connected via Bluetooth as well.

#### 4.2.2 Method

To investigate if the concept of tactile waypoint navigation can overcome challenges of traditional, map-based navigation systems we conducted an experimental field study. Participants had to use the Tactile Wayfinder and a commercial navigation system to reach a destination in an urban environment (see Figure 4.5). The study took place on three consecutive Saturdays in May 2009 in the city centre of Oldenburg. With its narrow, winding alleys the layout of the city centre is complex and even residents sometimes have their problems in orienting themselves. We chose Saturdays because the city centre is most crowded on weekends. We believed that the disadvantages of being distraction would be most evident in a complex layout and a crowded environment. In particular we investigated the the following hypotheses:

- **H4.1.1:** The Tactile Wayfinder allows travellers to pay more attention to the environment.
- **H4.1.2:** Consequently, the Tactile Wayfinder supports a better understanding of the environment.
- **H4.1.3:** The Tactile Wayfinder will be at a par with the vision-based baseline navigation system.



*Abbildung 4.5: A participant familiarises himself with the Tactile Wayfinder.*

#### 4.2.2.1 Material

Two routes were created for the field study. Each route was about 800 m long and contained six decision points. Both routes did not represent the shortest path to the destination and included unexpected detours. Thus, good knowledge about the city centre was not privileged as it was impossible to anticipate how the route would proceed beyond what the navigation system showed.

As commercial navigation system, we chose TomTom<sup>3</sup> since at the time the study took place it was one of the few state-of-the-art of pedestrian navigation systems. In a pilot test, we investigated how to configure TomTom most optimal. We found that map matching worked well in most cases. Sound was however turned off, as the pilot testers found it embarrassing and too hard to perceive. We configured TomTom to make use of the same type of bluetooth GPS receiver that the Tactile Wayfinder used. This ensured that the quality of the user position information was similar for both navigation systems.

#### 4.2.2.2 Participants

Fourteen participants, seven female and seven male, took part in the study. The age ranged from 20 to 30 with a mean age of 25.33 (SD 4.51). None of the participants had previous experience with the tactile belt. In average, they rated their familiarity with the city centre to be slightly above average (2.71, SD 1.38 on a scale from 1 = very good to 5 = very bad). We also assessed their sense of direction through the Santa Barbara Sense of Direction (SBSOD) Scale by Hegarty et al. [HRMS02]. This questionnaire consists of 15 statements to which the level of agreement can be indicated with a seven-point

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<sup>3</sup> <http://www.tomtom.com/>

Likert scale. It provides a score between 0 (no sense of direction) to 100 (perfect sense of direction). In average, our participants showed a neutral sense of direction ( $M = 50.57$ ,  $SD = 17.62$ ). All participants signed an informed consent prior to the study. They were not paid for their participation.

#### 4.2.2.3 Design

The navigation system served as independent variable. The Tactile Wayfinder fielding Spatial Tactons represented the experimental condition. TomTom with its visual display was used as control condition. The study used a within-subjects design. Thus, all participants contributed to both conditions. The order of conditions was counter-balanced to avoid sequence effects. The following dependent measures were taken in order to evaluate the acquisition of spatial knowledge, level of distraction, and the navigation performance:

##### Spatial Knowledge Acquisition

The acquisition of spatial knowledge was measured by two tests that have been reported by Aslan et al. [ASB<sup>+</sup>06]. While the *photo recall test* is more focussed on landmark knowledge the *route drawing test* examines the survey knowledge. The *photo recall test* requires participant to recall how they turned at different decision points along route. These decision points are presented on photos and participants have to mark if they turned left, right, or went straight (if applicable). The score is taken by summarising the number of wrong answers. In the *route drawing test* the participants had to reproduce the route they just walked on a sheet of paper. As a reference, the sheet showed the starting point, the destination, and the outer bounds of the city centre. To determine the score for this test, we measured how accurate in terms of centimetres the waypoints of the route were drawn compared to a map of the city centre.

##### Level of Distraction

The level of distraction was measured by assessing the subjective workload and counting how often the participants experienced near-accidents. Near-accidents were defined as situations where a participant collided with an obstacle, or when they had to suddenly change direction to avoid such a collision. The subjective workload was assessed through self-report using the Nasa Task Load Index (TLX) [HS88]. We assumed that a higher mental workload would go along with paying less attention to the environment.

##### Navigation Performance

The performance of the navigation task was measured in terms of completion time, disorientation time, and number of navigation errors. Disorientation events were counted when a participant explicitly mentioned to have lost orientation or when the participant

stood still for more than 10 seconds. The event was considered ongoing until the participant continued to walk into the correct direction. Navigation errors were counted when the participants entered a street they were not supposed to. The completion time was the time it took the user to reach the destination.

#### 4.2.2.4 Procedure

For each session the experimenters and the participants met near the starting point of the first route at a well-known place. Before starting the actual evaluation, the participants had to fill out a questionnaire providing demographic information, judging their familiarity with the city centre, and answering the SBSOD items. The participants also learned that they had to complete spatial knowledge tests so they should pay attention to the route. The experimenters then explained the Tactile Wayfinder to the users and demonstrated the use of TomTom. The participants tested both devices before the measurements started. In alternating order, one of the navigation systems was then chosen for the first route. During the navigation task, the participants were asked to hold the GPS receiver in their hands during the evaluation. This was done to avoid the GPS signal being further distracted by being inside a pocket close to the body. Two experimenters followed the participants in some distance and noted near-accidents, navigation errors, and the number and length of disorientation events (for the last measure they were equipped with a stop-watch). When the participants arrived at the end of the first route they were asked to perform the two spatial knowledge tests (photo recall and route drawing) and rate the subjective workload. Then, the navigation system was changed and the participants started with the second route. Arriving at the second route's destination, the participants performed the spatial knowledge tests and filled out the Nasa TLX again.

### 4.2.3 Results

Since the experiment had two conditions and a within-subject design, the collected data was tested for statistically significant differences using repeated-measures t-tests (two-tailed).

#### 4.2.3.1 Spatial Knowledge

The score for the photo recall test was calculated by counting the number of wrong turning directions in the participants' responses. If the participants did not remember how they turned at an intersection shown on a photo we counted an error as well. If participants approached the decision point from an unexpected direction due to a previous navigation error, we compared the participants' answers to how they actually had turned.

The results of the photo decision point recall test are shown in Figure 4.6. We found no significant difference between number of errors between TomTom ( $M = .79, SD = 1.12$ ) and Tactile Wayfinder ( $M = .64, SD = 1.15$ ), ( $p = .34$ ).

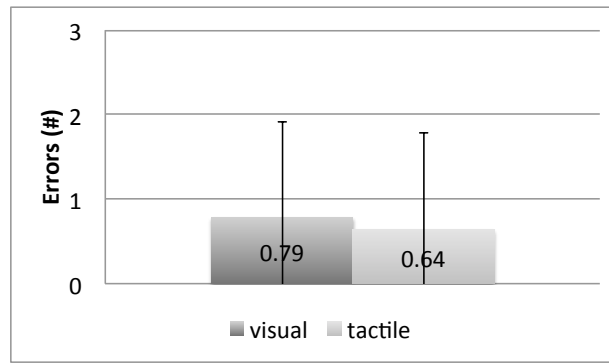


Abbildung 4.6: The results of the photo recall test showing the average number of errors per condition (no significant effect found).

Figure 4.7 shows one of the route drawings of the participants. The quality of these reproduced routes was quantified by comparing it with the actual route. We therefore scanned the drawings, printed them on transparent material, and put in on a map with the same scale. The distance in cm between each drawn waypoint and its correct counterpart served as error score.

Figure 4.8 shows the average drawing error for both conditions. We found no significant difference between the accuracy in cm between TomTom ( $M = 8.02, SD = 3.39$ ) and Tactile Wayfinder ( $M = 9.25, SD = 5.61$ ), ( $p = .27$ ).

The participants' scores in the spatial knowledge tests had a small/medium correlation with the sense of direction SBSOD score ( $r = -.21$  and  $r = -.30$ ). This means that participants with a good sense of direction also had higher scores in both spatial knowledge tests.

#### 4.2.3.2 Level of distraction

The level of distraction was estimated by the NasaTLX scores and the number of near-accidents. As suggested in [HS88] we asked the participants to rate importance of each NasaTLX item for the navigation task. All possible pairs of items were presented and the participants had to choose the more important one. Mental demand and frustration were rated most important. Physical and temporal demands were rated least important.

Figure 4.9 shows the average NasaTLX scores. The scores were normalised to a range of 1 (no workload) to 7 (high workload). We found no significant difference between the Nasa TLX scores between TomTom ( $M = 2.78, SD = 2.02$ ) and Tactile Wayfinder ( $M = 2.65, SD = 1.63$ ), ( $p = .40$ ).

Figure 4.10 shows the number of near-accidents. There was a significant effect of the navigation system on the number near-accidents ( $p < .05$ ). More near-accidents occurred in the TomTom condition ( $M = .79, SD = .89$ ) than in the Tactile Wayfinder



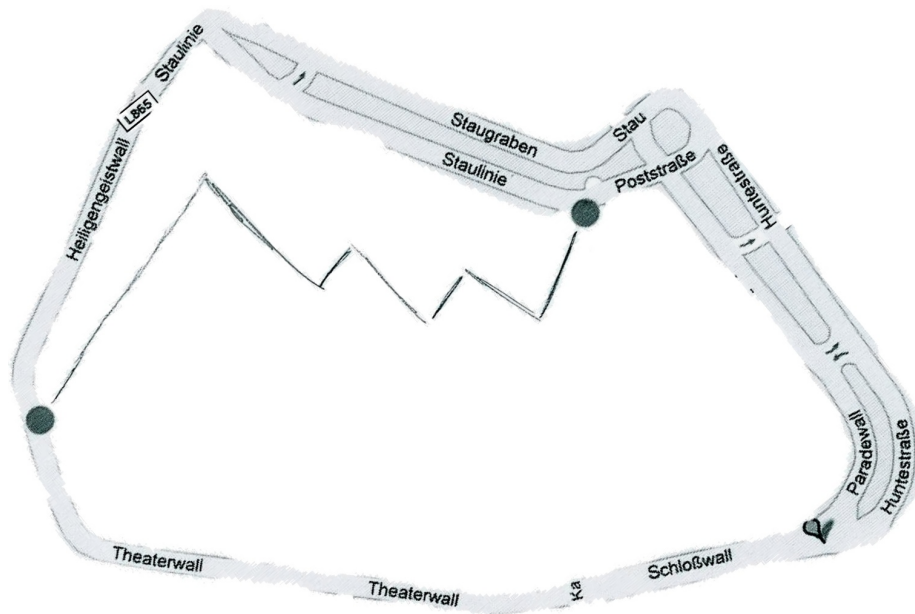


Abbildung 4.7: One of the routes drawn by a participant after the evaluation. How accurate the participants could reproduce the routes were used to compare the spatial knowledge between the two conditions.

condition ( $M = .14, SD = .36$ ). These results suggest that Tactile Wayfinder users were less distracted from their immediate surroundings.

There was also a noteworthy correlation between the sense of direction and the number of near-accidents. The seven participants with the lowest SBSOD score had 1.43 near accidents while those seven with the highest SBSOD only experienced 0.14 near accidents. Comparing the results of those groups statistically revealed a significant difference ( $p < .001$ ).

#### 4.2.3.3 Navigation Performance

The navigation performance was measured by the completion time, the number of navigation errors, and the time the participants were disoriented. Figure 4.11 shows the average completion time per condition. We found no significant effect on completion time (s) between TomTom ( $M = 762, SD = 129$ ) and Tactile Wayfinder ( $M = 840, SD = 135$ ), ( $p = .09$ ).

Figure 4.12 shows the average number of navigation errors per condition. There was a significant effect of the navigation system on the number of navigation errors ( $p < .01$ ). Less navigation errors occurred in the TomTom condition ( $M = .29, SD = .61$ ) than in the Tactile Wayfinder condition ( $M = .93, SD = .83$ ). These results suggest that TomTom users made less navigation errors.



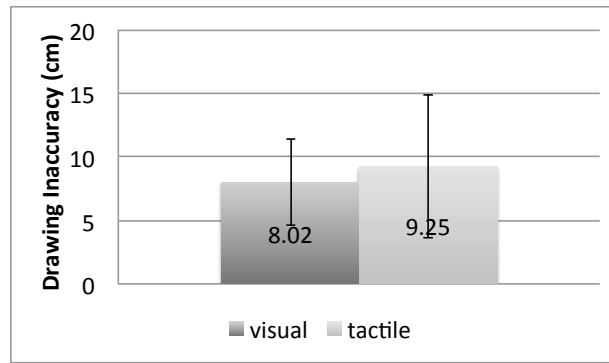


Abbildung 4.8: The results of the route drawing tests showing the accuracy of the drawings per condition (no significant effect found).

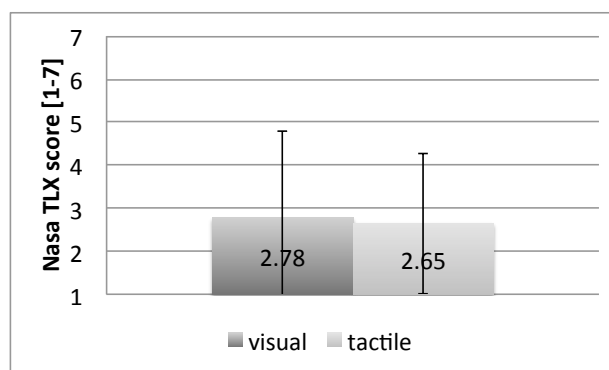


Abbildung 4.9: The NasaTLX scores per condition (no significant effect found).

Figure 4.13 shows the average time the participants were disoriented per condition. We found no significant effect on disorientation time (s) between TomTom ( $M = 23.7$ ,  $SD = 29.0$ ) and Tactile Wayfinder ( $M = 36.0$ ,  $SD = 41.3$ ), ( $p = .12$ ).

Completion time and time being disoriented were highly correlated ( $r = .77$ ). Thus, participants who often lost orientation were very likely to need more time to complete the route. The number of navigation errors and the waypoint position errors while re-drawing the route were highly correlated ( $r = .73$ ). Therefore, participants who made many navigation errors were also more likely to draw the walked route more inaccurately.

#### 4.2.3.4 Gender Differences

We also looked for gender differences. In the control condition, no significant differences were found. However, in the experimental condition there were significant differences in the navigation performance between the genders. In average, female participants took

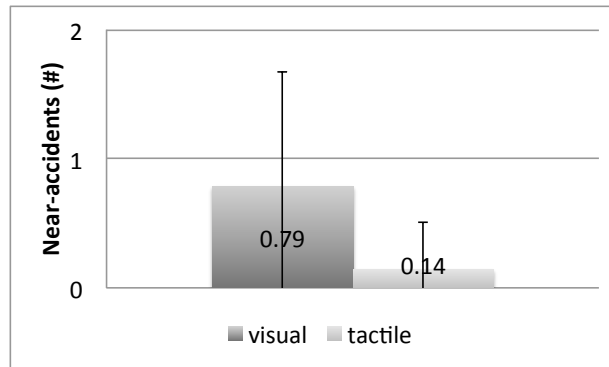


Abbildung 4.10: The number of near-accidents per condition. The Tactile Wayfinder significantly reduced the number of near-accidents.

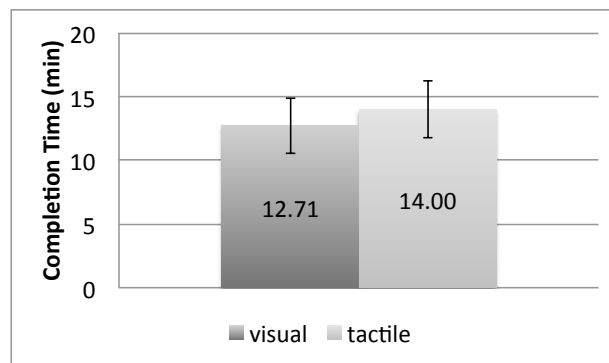


Abbildung 4.11: The average completion time per condition (no significant effect found).

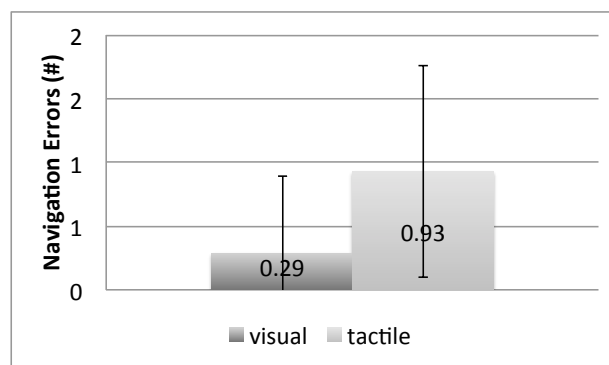


Abbildung 4.12: The average number of navigation errors per condition. The Tactile Wayfinder significantly increased the number of navigation errors.

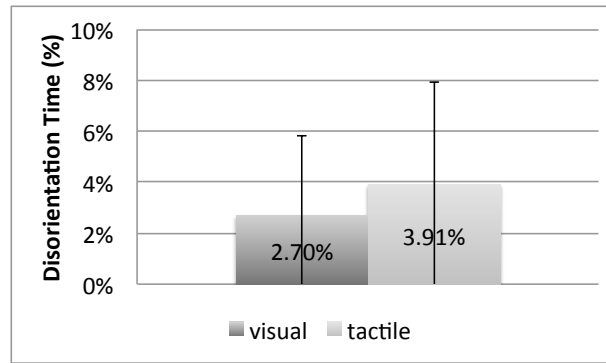


Abbildung 4.13: The average time being disoriented per condition (no significant effect found).

longer to complete the routes ( $p < .01$ ), made more navigation errors ( $p < .05$ ), and lost their orientation more often ( $p < .05$ ), as shown in table 4.1.

	Completion Time (s)	Navigation Errors	Disorientation Count
Female	925	2.43	3.29
Male	754.29	0.71	1.29

Tabelle 4.1: The navigation performance with the Tactile Wayfinder split by gender.

#### 4.2.3.5 Comments and Observations

Regarding TomTom the participants mainly concentrated on the route and their position shown on the map to navigate. To our surprise, none of the participants seemed to follow the turning instructions. This was a good idea since GPS was sometimes considerably inaccurate. It even occurred that TomTom's map matching algorithm located people in the wrong street. Since the tactile belt employed a compass while TomTom depended on the GPS positioning update, there was a notable delay in updating the route. This turned into a problem for some of the participants as they turned into a new street but it took TomTom a few seconds to reflect that new situation. So, beyond each turning point there was a short period of "blind navigation".

Seven of the 14 navigation errors with the Tactile Wayfinder occurred at a y-formed junction of the second route where two paths continued almost in parallel direction. The tactile direction cueing combined with GPS inaccuracies seemed to be too coarse for the participants to clearly decide for one of the path. In some cases this caused the participants to choose the wrong path. This did not cause too much delay, since there was a connection between the two paths later on.

Regarding the subjective workload, the participants had divergent opinions: one half

expressed that they found it exhausting to focus on the tactile cues. The other half stated that they could pay more attention to the environment. Participants complained quite often that wearing the belt was uncomfortable due to the constant tactile feedback. Some suggested a tactile volume control or a pause function in order to be able to reduce the amount of feedback. Many participants missed a map to get an overview about their environment. One of the most prominent complaints was that the participants felt to be patronised by the Tactile Wayfinder.

#### 4.2.4 Discussion

In summary, both navigation aids enabled the participants to reach the given destinations. No difference in the participants' spatial knowledge acquisition could be found between the Tactile Wayfinder and TomTom. Using the Tactile Wayfinder the participants experienced fewer near-accidents but made more navigation errors. Having a better sense of direction correlated with fewer near-accidents and better spatial knowledge acquisition. Male participants had a better navigation performance with the Tactile Wayfinder than female participants.

The results confirm **H4.1.1** (*Tactile Wayfinder allows travellers to pay more attention to the environment*). The Tactile Wayfinder allowed participants to spend significantly more attention to the environment so they were less likely to (nearly) collide with other people or obstacles. These findings confirm the predictions by Wickens' Multiple Resource Theory [Wic84] or van Erp's Prenav model [vE07] that conveying information via different senses reduces the overall cognitive workload. They also go conform with the results of Duistermaat et al. [DEvER07]. The subjective workload did however not decrease significantly. One explanation could be that the participants had to focus on the tactile output every now and then as there was no other source of directions. This goes along with the complaint that some participants felt to be patronised by the Tactile Wayfinder. This could be countered by giving the participants a better overview of their situation, e.g. by combining tactile feedback with maps, as proposed in [StBNL08, PHB09]. There was also a high correlation between a good sense of direction and few near-accidents. Thus, participants with a bad sense of direction paid less attention to the environment. It therefore seems important to specifically consider the group of users with a bad sense of direction in navigation system design.

Regarding **H4.1.2** (*Consequently, the Tactile Wayfinder supports a better understanding of the environment*), we could not find significant effects of the type of feedback. Both spatial knowledge tests were not significant. Thus, the egocentric visualisation of the two upcoming waypoints could not improve the spatial knowledge acquisition compared to the traditional, map-based navigation system. Instead, having a good sense of direction went along with better spatial knowledge scores. The sense of direction might therefore play a more important role in understanding the spatial layout of an environ-

ment than the actual navigation aid. Therefore, navigation aid designers should consider how to improve the general sense of direction along with the navigation instructions.

With respect to **H4.1.3** (*The Tactile Wayfinder will be at a par with the vision-based baseline navigation system*), the results suggest that the navigation performance was worse with the Tactile Wayfinder. The participants made significantly more navigation errors with the Tactile Wayfinder. The high correlation between completion time and disorientation events suggest that the participants lost most of their time when they were disoriented. On the other hand, this suggests that both navigation systems performed similar when the participants were well oriented.

The results also indicate that female participants had more problems navigating with the Tactile Wayfinder. Since gender is no independent-variable, gender-related results have to be analysed carefully. A simple explanation might be that the male participants were more tech-savvy in average. Another more interesting explanation can be found in the use of different wayfinding strategies reported in the literature. According to Lawton [Law94] women prefer a wayfinding strategy based on route-knowledge (e.g. at the shop turn left) while men prefer a survey-knowledge strategy (e.g. keep track of the own position on a map). Assuming our participants applied the respective wayfinding strategies, tactile waypoint navigation might not be compatible with route-knowledge-based strategies.

#### 4.2.5 Conclusions

We investigated using Spatial Tactons to deliver turn-by-turn navigation instructions via a tactile belt to address the challenge of distraction. In order to provide travellers with an overview of the route, we advanced previous approaches of waypoint navigation by conveying the location of two instead of a single waypoint at the same time. In a field study conducted in an urban environment, a traditional, map-based navigation system (TomTom) was compared with our Tactile Wayfinder in a navigation task. We could replicate previous findings that tactile information presentation can reduce cognitive load. On the other hand, the Tactile Wayfinder was outperformed by the commercial navigation system in terms of navigation errors.

The users' sense of direction turned out to be closely related to most of our results. A better sense of direction correlated with better spatial knowledge acquisition and a positive effect on the users' cognitive workload. In addition, a better completion time was highly correlated with less disorientation events. Also, users felt patronised by only receiving turn-by-turn instructions but having no overview about the environment. The results also let us suggest that wayfinding based on survey knowledge (keeping track of the own location in related to reference points) is correlated to a more successful navigation performance. Thus, being well oriented is important for spatial knowledge acquisition, cognitive workload, and navigation performance.

In summary, Spatial Tactons have shown to decrease the level of distraction as predicted by models of human information processing. Yet, the results leave room for improvements. They suggest that simply replacing visual turn-by-turn navigation systems with tactile counter-parts might not be the best approach. Instead we might be looking into how to support the users' sense of direction during the travel. In particular, combining a (visual) overview map and tactile turn-by-turn instructions might be a viable approach.

### 4.3 Eyes-Free Pedestrian Navigation with a Tactile Compass

The material in this section originally appeared in Pielot, M.; Poppinga, B.; Heuten, W. & Boll, S. 6th Senses for Everyone! The Value of Multimodal Feedback in Handheld Navigation Aids *ICMI 2011: 13th International Conference on Multimodal Interaction*, 2011

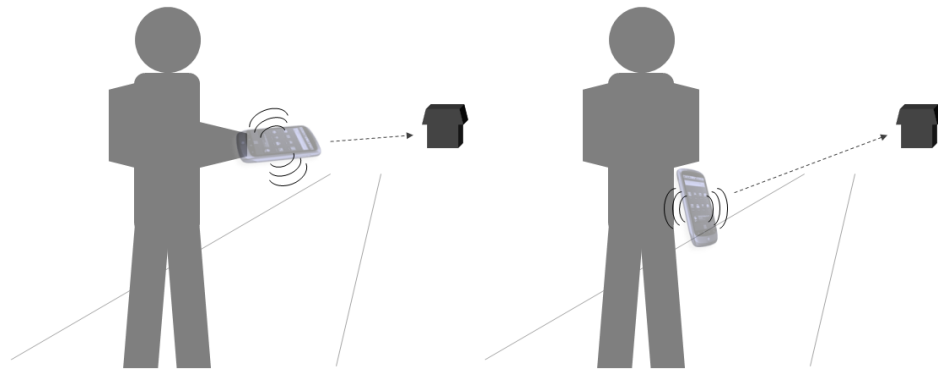
This section reports from a field study conducted with the Tactile Compass. The study experimentally compared visual, tactile, and multimodal turn-by-turn navigation instructions with a handheld pedestrian navigation system. Data from 21 participants and 63 routes were collected. The results provide evidence that the distraction could be reduced by providing tactile feedback only. Advancing the findings from the previous study with the Tactile Wayfinder the results also suggest the combining visual turn-by-turn instructions and Spatial Tactons can improved the navigation performance.

#### 4.3.1 Waypoint Navigation with the Tactile Compass

In the previous study we have compared Spatial Tactons delivered by a Tactile Belt with a commercial pedestrian navigation aid. However, Tactile Belts might not always be available when the user is travelling. User might also just not want to carry such a device if navigation support is not required too often. Therefore, researchers have investigated whether navigation support can also be provided with the most ubiquitous tactile display: the vibration alarm of mobile phones. There are two predominant solutions, which Frohlich et al [FOBN11] refer to as the *magic wand* and *sixth sense*.

The *magic wand* metaphor, as illustrated in the left of Figure 4.14, follows the idea that a user points at a distant object with a handheld device to learn about its presence or access information about it. Technically this is possible as nowadays smartphones are equipped with a digital compass. Recent implementations provide feedback when the user roughly points into the correct direction of a relevant geographic location, such as the travel destination [MMRGS10, RJE<sup>+</sup>10, WRS<sup>+</sup>10]. Thus, by actively scanning the environment the user can stay aware of the general direction of her or his travel destination. It has been shown that this technique is very intuitive and allows users to effectively reach a given destination [MMRGS10, RJE<sup>+</sup>10, WRS<sup>+</sup>10]. However, the intuitiveness

is traded with the drawback that the device has to be held in the hand and actively needs to be pointed at the object, which has been found undesirable by some users [RJE<sup>+</sup>10].



(a) Magic Wand metaphor: user learns about location of an object by pointing at it with a mobile device. (b) Sixth Sense metaphor: location of an object is encoded in e.g. vibration patterns.

Abbildung 4.14: Two approaches of conveying spatial information by mobile phones proposed by Frohlich et al.

The *sixth sense* metaphor, as illustrated in the right of Figure 4.14, describes solutions that use multimodal feedback to alert the user about changes in the environment. One example of this is the Tactile Compass we proposed in Section 3.2. In the context of waypoint navigation it can e.g. be used to indicate the location of the next waypoint.

Both approaches have proven to be effective in user studies. Also, both approaches have complementing advantages: the magic wand has found to be very intuitive while the Tactile Compass has to be learnt. On the other hand, the Tactile Compass can be used without performing pointing gestures, which have been found to annoy users over time [RJE<sup>+</sup>10]. Therefore, we combined both approaches for this study.

As instance of the magic wand metaphor we used the pointing design proposed by [RJE<sup>+</sup>10, WRS<sup>+</sup>10, MMRGS10], which allows the user to scan for a geographical entity by pointing gestures. When the device e.g. points at the next waypoint, this waypoint is considered being "ahead".

As instance of the sixth sense metaphor we used the Tactile Compass proposed in Section 3.2 to provide the direction of the next waypoint in vibration patterns. When the user e.g. walks towards the next waypoint, two short pulses indicate "ahead" (see Fig. 4.15 for all eight vibration patterns).

Technically the tactile information presentation techniques are applied as waypoint navigation techniques [EvERD10, PPB10]. Therefore, routes are divided into sets of waypoints. The system constantly conveys the direction of the waypoint that has to be reached next. Once this waypoint has been reached the system switches to the subsequent waypoint. The user is thus dragged along the route until reaching the destination. In our

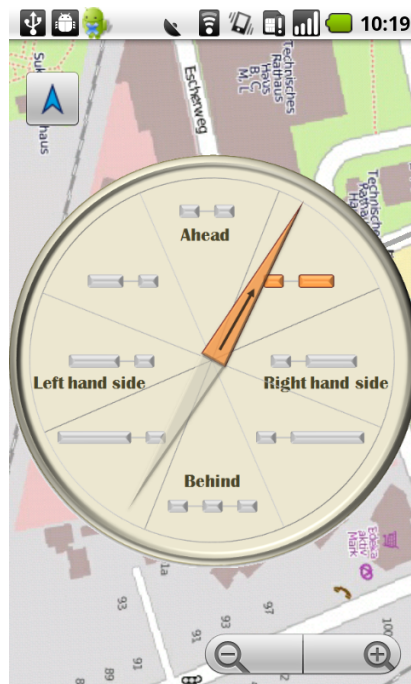


Abbildung 4.15: Screenshot of the PocketNavigator and the Tactile Compass used in this study.



particular implementation we also allowed the user to skip waypoints when e.g. going cross country, finding a shortcut, or simply taking a wrong turn.

The success of waypoint navigation also depends on how close the user needs to get to a waypoint until the system switches to the subsequent waypoint. Switching too late causes the user to reach the decision point without knowing where to go. Switching to the next waypoint too early can result into direction information that may be hard to interpret, since e.g. the system points at a building. In a series of pilot studies we optimised the switching time to provide the new directional information in the most suitable moment. One of the tweaks we used was to switch to the next waypoint earlier, the faster the user walked and the less accurate the GPS signal was.

#### 4.3.2 Method

To study these novel handheld-based interaction techniques [LCY08, MMRGS10, PPS<sup>+</sup>11, RJE<sup>+</sup>10, WRS<sup>+</sup>10] in multimodal usage we conducted a field experiment. 21 participants were asked to navigate through a crowded urban environment, namely the city centre of Oldenburg. In three conditions, they were equipped with either a handheld-based tactile navigation system, or a state of the art pedestrian navigation system, and the combination of both. We wanted to investigate the following hypotheses:

- **H4.2.1:** The Tactile Compass will reduce the level of distraction.
- **H4.2.2:** The Tactile Compass will create lower cognitive workload.
- **H4.2.3:** The navigation performance will be best when both systems are used in combination.

##### 4.3.2.1 Evaluation Environment

The study was conducted in the summer of 2010. It took place in the pedestrian zone of Oldenburg, a European city with about 150,000 inhabitants. The winding layout of the streets makes it difficult to stay oriented, even for locals. During shopping hours the city centre becomes very crowded, so a lot of attention is required to evade other people and obstacles. We defined two training routes and three evaluation routes (see Fig. 4.16). Each route covered about 450 meters. All routes started and ended in calm, less frequented areas and led through the central, most crowded area.

##### 4.3.2.2 Navigation System

For the experiment we used a self-developed navigation system called PocketNavigator [PPB10], which is similar to Google Maps. We did our own implementation to be able to tightly integrate the Tactile Compass into the system, ensure equal technology



Abbildung 4.16: The three evaluation routes covering the city centre of Oldenburg (the two test routes are not shown). Map by OpenStreetMap.org

in all experimental conditions, and provide OpenStreetMap data which - unlike Google Maps - has all pedestrian paths available. Otherwise, the PocketNavigator provides all the relevant functionality available in Google Maps: the user's position and orientation is indicated by an icon drawn onto the map. The map can be set to automatically rotate and align itself with the environment, so the *up* direction on the screen corresponds to the device's orientation. The route is highlighted on the map. Additionally an arrow icon in the bottom left corner of the screen visually indicates into which direction to go. Figure 4.17 shows a screenshot illustrating these features. In pilot studies we learned that many users feel embarrassed and distracted by speech output, especially in lively areas. Therefore, only visual feedback was provided.

#### 4.3.2.3 Participants

Twenty-one participants (10 female, 11 male) took part in the study. Their age ranged from 18 to 41 with an average of 26.6 years ( $SD = 6.68$ ). Prior to the study we assessed the participants' familiarity with (pedestrian) navigation systems and their sense of direction. The sense of direction was assessed by the Santa Barbara Sense of Direction Scale (SBSOD) [HRMS02]. In a possible range from 1 (low) to 100 (high) the participants scored 54.72 ( $SD = 15.37$ ) in average. The participants judged their familiarity to be average with car navigation systems ( $M = 3.05, SD = 1.02, [1 = low - 5 = high]$ ) and below average with pedestrian navigation systems ( $M = 1.95, SD = 1.16, [1 = low - 5 = high]$ ). Although no personally identifiable information was collected all participants signed an informed consent. All participants received a gift to compensate their participation in the study.

#### 4.3.2.4 Design

The navigation system configuration served as independent variable with three levels: *visual*, *tactile*, and *combined*. In the *visual* condition the participants only used the visual

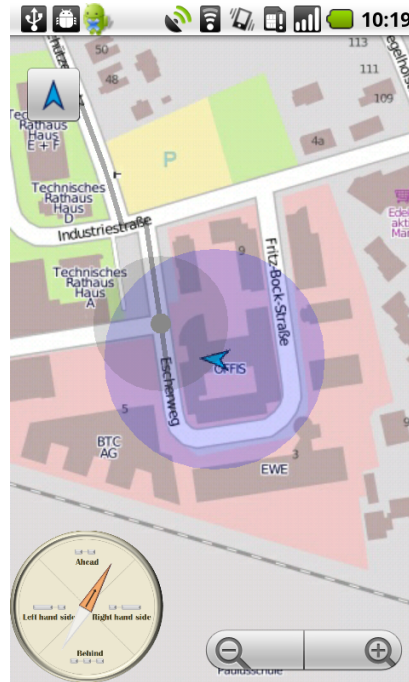


Abbildung 4.17: Screenshot of the PocketNavigator as used in the visual condition.

feedback of the navigation system. In the *tactile* condition the screen was blinded so only the tactile feedback could be used. In the *combined* condition, both, the tactile feedback and the visual feedback were available.

The experiment followed a within-subjects design, so every participant contributed to all three conditions. The order was counter-balanced to cancel out sequence effects. The following dependent measures were taken to assess the navigation performance, the cognitive workload, and the level of distraction:

### Navigation Performance

Inspired by previous field studies (e.g. [IFIO08, RMH09, PB10b]) navigation performance was measured in terms of completion time, number of navigation errors, number of orientation phases, and number of orientation losses. *Completion time* was defined as the time the participants travelled from start to end of each route. A *navigation error* was counted when a pedestrian took a wrong turn and entered the wrong street for more than 5 meters. *Disorientation events* were defined as situations where the participants stopped for more than 10 seconds or stopped and expressed their disorientation verbally. An *orientation phase* was counted when the participant stopped shortly (less than 10 s) to re-orient themselves.

### Cognitive & Mental Workload

The cognitive workload was measured by subjective and objective measures. As subjective measures we issued the widely accepted Nasa TLX [HS88] questionnaire in a scientifically validated, localized version. As objective workload measure we monitored the participants' walking speed, as Brewster et al. [BLB<sup>+</sup>03] suggested that people walk slower when the cognitive workload increases while interacting with a handheld device. The walking speed was extracted from the GPS signal.

### Distraction

The distraction was quantified by measuring how much participants interacted with the mobile device and how well they could pay attention to the environment. To assess how well the participants paid attention to the environment we asked the participants to count the number of cafes, hair dressers, and pharmacies and name the sum of all of these shops at the end of the route. Since the experimenters were aware of all of these shops they could calculate the ratio of how many shops have been detected. Interacting with the device was divided into two groups: looking at the map and using the pointing gestures. The participants were considered *looking at the map* when the device was held in an angle that allowed that participant to look at the display. The participant was considered *pointing* when the device was held nearly parallel to the ground. Since in the *combined* condition the user could also be looking at the map when pointing and vice versa, such situations were contributing to both dependent measures at the same time. How the device was held was logged automatically by the device, so these measures could be taken without having to use a video camera.

#### 4.3.2.5 Procedure

Informed consents, demographic questionnaires, and additional information were sent out to the potential participants prior to the study. Only those participants who signed the consent forms were invited to the study.

Training sessions allowed the participants to get used to the navigation system. A dedicated application was developed to train the tactile feedback. It allowed the participants to explore and learn the different patterns. To complete the learning phase, at least 75 % of the patterns in a set of 16 random directions had to be recognized correctly. Afterwards the participants could train the use of the application on two test routes. The first test route was done with visual and tactile feedback, the second with tactile feedback only. During both test routes we trained the participants to use the pointing gesture or to look at the device' screen only when needed and otherwise keep the device in a position where the arm was relaxed.

When the actual evaluation started we explained the participants that they had to count cafes, hair dressers, and pharmacies they pass by on their route. The navigation time started to be recorded when the route was selected on the mobile device. The experimenter

followed the participant in some distance and noted navigation errors, orientation losses, and orientation phases. The experimenter also watched out for the number of shops to be counted when participants left the correct route due to a navigation error. When arriving at the last waypoint of the route the completion time was automatically taken. The participants filled out the Nasa TLX for the past condition and then switched to the next condition.

After having completed all three routes we conducted an open post-hoc interview with the participants. The goal was to learn about any of the participants' impressions and suggestions. Our strategy was to not ask any question unless the interview went stuck but encourage the participants to express their thoughts freely. The whole procedure took about 90 minutes for each participant.

### 4.3.3 Results

All participants succeeded to reach the destination in all three conditions. In the following we present the quantitative and qualitative findings.

#### 4.3.3.1 Quantitative Results

This section presents the quantitative results of the dependent variables. The diagrams show mean value and standard deviation per condition. Statistical significance was analyzed using ANOVA and Tukey post-hoc tests.

##### Navigation Performance

Figure 4.18 shows the navigation performance by condition. No significant effects could be found on the *completion time* ( $F(2) = 2.93, p = .06$ ) and the number of *orientation losses* ( $F(2) = 0.47, p = .63$ ). There was a significant effect on the number of *navigation errors* ( $F(2) = 3.65, p < .05$ ). In the *combined* condition participants took less wrong turns than in the *visual* or the *tactile* condition (both  $p < .05$ ). Further, there was a significant effect on the number of *orientation phases* ( $F(2) = 4.93, p < .01$ ). In the *tactile* condition the participants made more short stops than in the *visual* condition ( $p < .01$ ). In summary, participants stopped more often to reorient when using the tactile feedback only. The multimodal combination of visual and tactile led to less navigation errors.

##### Cognitive Workload

Figure 4.19 shows the results related to the cognitive workload. There was a significant effect on the participants' walking speed ( $F(2) = 5.01, p < .01$ ). Participants walked faster in the *visual* condition than in the *tactile* condition ( $p < .01$ ) and in the *combined* condition ( $p < .05$ ). Thus, the objective cognitive workload was higher when

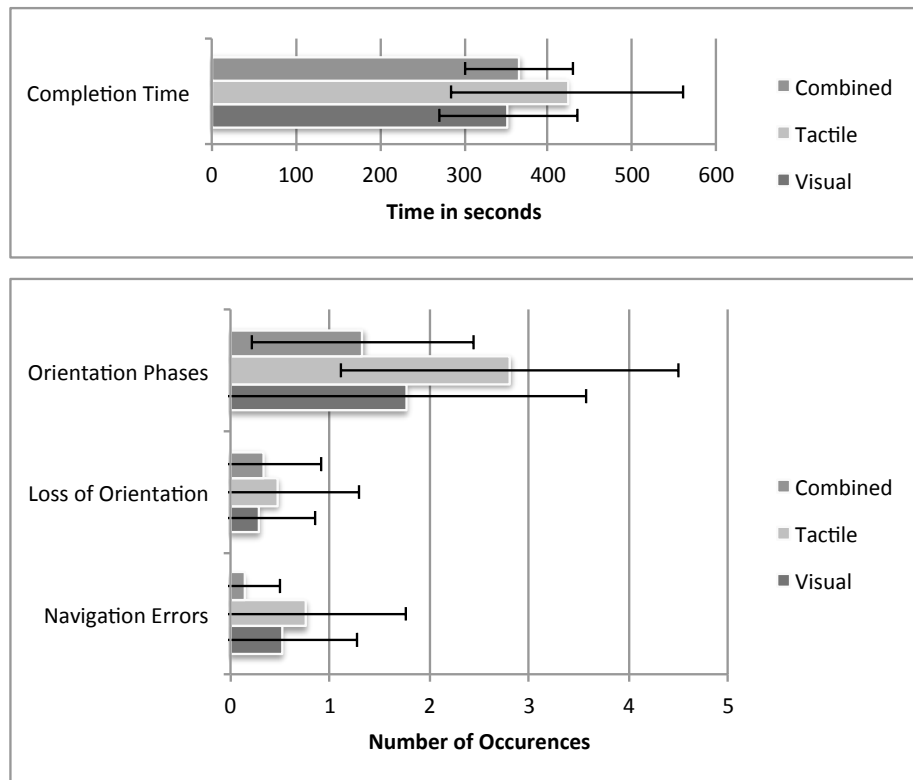


Abbildung 4.18: Navigation performance measures.

the tactile feedback was present. However, the subjective judgement of the cognitive workload via the NasaTLX showed no significant differences between the conditions ( $F(2) = 1.04, p = .36$ ).

#### Distraction

Figure 4.20 shows the results related to the distraction. There was no significant effect on the number of shops found ( $F(2) = .94, p < .40$ ). But, there was a significant effect on the amount of interaction ( $F(2) = 3.41, p < .05$ ). The interaction was significantly lower in the *tactile* and in the *combined* condition than in the *visual* condition (both  $p < .05$ ). Considering only the time spent *looking at the map* in the conditions where the map was available, the participants in the *visual* condition looked significantly less often at the map compared to the *combined* condition ( $p < .05$ ). In the two conditions where the tactile feedback was present, the participants used the pointing gesture significantly less often in the *combined* condition than in the *tactile* condition ( $p < .01$ ). In summary, the visual feedback reduced the amount of pointing interaction and the tactile feedback had a positive effect on the amount of distractive interaction.

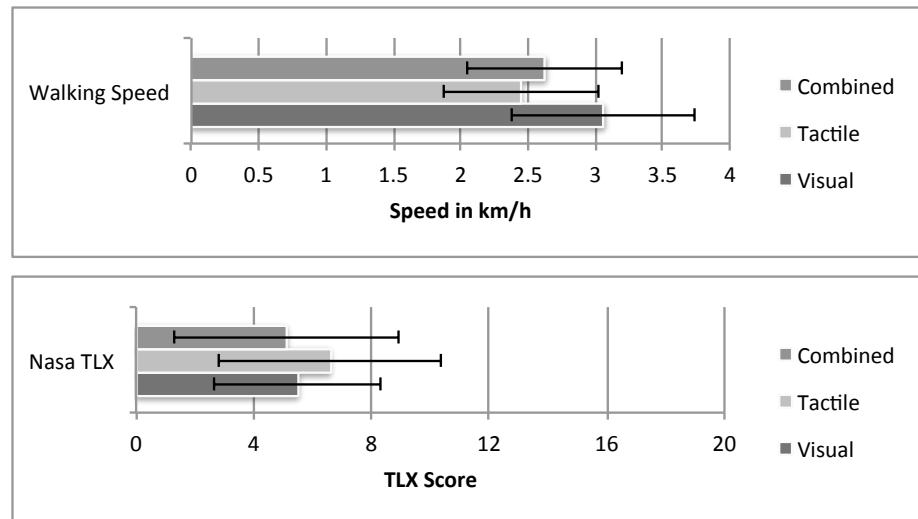


Abbildung 4.19: Cognitive workload measures.

#### 4.3.3.2 Comments and Observations

In the beginning of the experiment, many participants were questioning whether the tactile feedback only was sufficiently easy to use. During the study, however, none of the participants failed interpreting the tactile cues. One participant nicely summarized this by stating: *when reading the information sheets I never thought these vibration patterns would work. But in retrospect, it was much more intuitive than I expected.*

#### Navigation Strategies

**Visual Condition** In the *visual* condition the predominant strategy was "read 'n' run": the participants studied the map, memorized the upcoming route segment, and then passed the memorized part as quickly as possible without looking at the map. Participants using this strategy were walking faster than in any other situations we observed. Since the study took place in summer, sunlight reflections were one of the major issues in reading the map. Three participants reported to have major trouble with reading the display (see Fig. 4.21).

**Tactile Condition** As suggested, the participants used the pointing gestures only when there was a specific need for more accurate information, such as when the GPS signal strength declined or when the participants wanted to reorient themselves at a crossing. Usually, the participants pointed the device forward into their walking direction. They tried to learn the direction of the next waypoint from the pattern rather than actively pointing the device in different directions to find the "ahead" pattern by pointing into different direction. Thus, the pointing interaction studied in [MMRGS10, RJE<sup>+</sup>10, WRS<sup>+</sup>10]

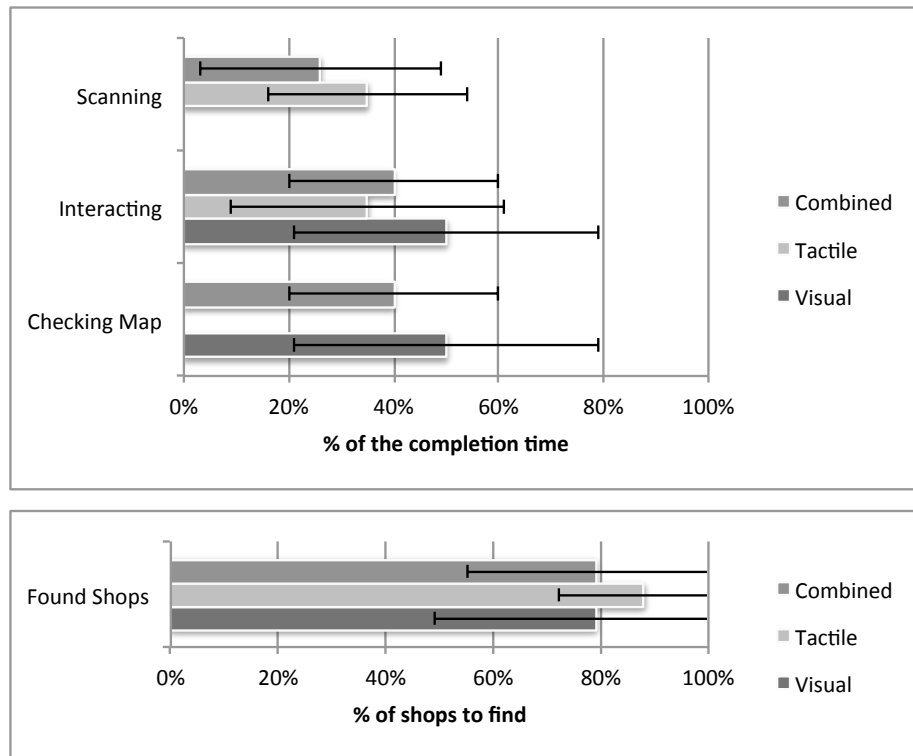


Abbildung 4.20: Distraction-related measures.

has rarely been observed. Although there was no technical need, there was a tendency that the participants stopped when doing pointing gestures.

In the post-hoc interview many participants stated that they found the tactile feedback surprisingly more easy to be used than they had expected. The lack of an overview was named five times as notable drawback. Four participants stated that they were missing the map to understand how the route proceeded beyond the next waypoint. However, regarding the *tactile* condition six participants expressed that they were not missing the map at all.

**Combined Condition** The combination of tactile and visual feedback was named most often as the preferred condition. The participants enjoyed to have the map to get an overview and at the same time receive constant confirmation by the tactile cues. Many participants focused on one source of information primarily and used the other as support. Eight participants reported to have relied on the map and used the tactile feedback to be reminded of an upcoming turn. Seven participants reported to have primarily used the tactile feedback and used the map only when being uncertain. Unlike the *visual* condition, the "read 'n' run" strategy was hardly observed in this condition.





*Abbildung 4.21: Participant struggling to read the display due to sunlight reflections (left). Participant scanning for the next waypoint (right).*

### Cognitive Workload and Distraction

Many participants stated that they were constantly monitoring the tactile feedback. Three participants explicitly mentioned that processing the constant feedback was mentally demanding. On the other hand, four participants appreciated the continuous feedback. They felt that people having bad sense of direction would greatly benefit from the constant confirmation.

With respect to the distraction, participants appreciated that the tactile feedback made it unnecessary to look at a display. Nine participants positively mentioned the private and eyes-free usage, in particular when the display is hard to read due to sunlight reflections.

### Tactile Compass Design

In order to identify areas of improvement we also asked people about the impressions with respect to the Tactile Compass. In the post-hoc interviews we identified two reoccurring issues:

The first issue was the number of directions to present. Our design cued eight directions in vibration patterns. However, seven participants stated that they mentally ignored the intermediate directions and therefore navigated by ahead, behind, left-hand side and right-hand side only. Additionally, five participants reported to have difficulties to dis-

criminate the *ahead* and the two adjacent directions (ahead/right - ahead/left). Three participants explicitly suggested reducing the number of directions to four.

The second issue was the constant presence of the tactile feedback. It was explicitly appreciated by four participants who felt to have a bad sense of direction. However, the bigger share of the participants pointed out that their attention was drawn too much by the constantly repeated vibration patterns. Some said that they could not stop listening for changes in the vibration signals. During the study we observed many cases, where the participants appeared to concentrate a lot on the tactile patterns (see e.g. Fig. 4.21). Suggestions for improvement were to play the tactile patterns only on the user's request or only in situations where it is necessary, e.g. when approaching a turn or when leaving the route.

#### 4.3.4 Discussion

All participants were able to reach the given destinations with the visual, the tactile, and the multimodal, combined feedback. The multimodal feedback improved the navigation performance by reducing the number of navigation errors. The tactile feedback only led to less distractive interaction with the handheld device. The presence of the tactile feedback in the *tactile* and the *combined* condition led to slower walking speeds, which we believe may be a sign for an increased cognitive workload.

The results confirm **H4.2.1** (*The Tactile Compass will reduce the level of distraction*). Complementing the visual system with tactile feedback helped reducing the time spent interacting with the device significantly. Compared to the *visual* condition the participants looked less often at the map. Compared to the *tactile* condition the participants used the pointing gesture less often. Taking the overall time spent scanning & looking on the map into account, the participants were interacting most when having visual feedback only. These findings show that the reduction of the user's distraction shown for tactile belts [EvERD10, PHB09, PPB10] also applies to the sixth sense and the magic wand metaphors for handheld devices.

However, although the participants found most shops in the *tactile* condition, no significant effect was found on the detection rate. This can be explained by the fact that the detection rates were generally high (between 77 % and 88 %). We therefore cannot confirm the findings by Elliott et al. [EvERD10] where soldiers could spot most "targets" with a tactile navigation system. However, Elliott et al. compared their tactile navigation system with a head-mounted display and an alphanumeric handheld GPS coordinate representation. Both baseline systems in their study presumably require more effort to interpret the navigation information than the navigation system used in our study. Thus, the findings by Elliott et al. might be confirmed when the tactile feedback is employed with improvements with respect to the cognitive workload and more training.

Regarding **H4.2.2** (*The Tactile Compass will create lower cognitive workload*), the re-

sults indicate that the tactile feedback actually induced cognitive workload. The walking speed was significantly higher in the *visual* condition which according to Brewster et al. [BLB<sup>+</sup>03] is a sign of less cognitive workload. Many participants who reported that they have been constantly feeling for vibration patterns confirmed this. Notably, this happened in the *tactile* and in the *combined* condition, although in the *combined* condition the participants could have used the system as in the *visual* condition by just ignoring the tactile feedback.

We are surprised that we did not observe an equivalent of the cocktail party effect, where people selectively listen to a single speaker while ignoring all other conversations and background noise. Our results indicate that even in the *combined* condition, where interpreting the tactile patterns was not necessary at all, the participants tried to interpret them. One explanation might be found in the work by Ho et al. [HTS05] who found that the sense of touch can be used to attract and direct the human's attention. The tactile cues could have attracted the users' attention even in situations where it was unnecessary. Future design iterations could address this issue by simplifying the tactile icons further (e.g. by reducing the number of directions) and providing information only when necessary. On the good side, these findings indicate that tactile cues are well perceived on the move and do not suffer from external interferences. So, tactile cues would be particularly effective in drawing the user's attention if required.

**H4.2.3** (*The navigation performance will be best when both systems are used in combination*) is supported by the results. The combination of both modalities could improve the navigation performance in terms of navigation errors. Similar findings have been made with body centric cues provided by tactile waist belts. In two studies [StBNL08, PHB09] it was shown that cueing the location of the destination can improve the navigation performance. However, there are two notable advancements: (1) the work presented here is based on abstract patterns and pointing gestures, not body centric cues. The latter are presumably easier to interpret. (2) in the reported studies the tactile displays were used in combination with maps. Here we provided turn-by-turn instructions, which require less interpretation and mental processing. Thus, we could show that navigation performance can still be increased, even if the tactile cues are less intuitive and the visual cues are more intuitive.

Our findings inline with previous research stating that cueing directions is possible with a single actuator and form effective navigation aids [MMRGS10, PPS<sup>+</sup>11, RJE<sup>+</sup>10]. Although no statistically significant differences could be observed, there was a tendency towards a decreased navigation performance in the *tactile* condition. We did not find this surprising given the fact that most participants had previous experience with visual navigation systems while the tactile system was completely new to them. Although we included two training routes, the question remains whether the performance would converge over time as the user gains more experience in using the tactile compass. In any case, the difference was not statistically significant, hence, it may be due to unsystematic variance.

### Limitations of the study

Some participants were not completely unfamiliar with the city centre. This could account for the "read'n'run" strategy we observed in the *visual* condition and thus have favoured the conditions with the visual feedback. In completely unfamiliar environments the tactile feedback might therefore have performed better in comparison. In particular, this shows that maps are distracting even though users already have some understanding of their content. In terms of ecological validity we do not see the results threatened, as it is not uncommon to use navigation systems in somewhat familiar environments.

### 4.3.5 Conclusions

In this study we investigated the Spatial Tactons delivered by the Tactile Compass for providing turn-by-turn navigation instructions. The presented study provides evidence that replacing visual feedback with tactile feedback can reduce a navigator's level of *distraction*. At the same time the results suggest that complementing visual feedback with tactile feedback can increase the navigation performance. Furthermore, we found an increased cognitive workload caused by the tactile feedback, which lets us conclude that the vibration patterns of the Tactile Compass induced cognitive workload.

These findings will allow tailoring navigation systems towards the context of use. If the goal is to reduce the level of distraction, offering a tactile-only mode is a suitable approach. If the goal is to improve the navigation performance, this can be achieved by combining tactile and visual cues. The findings may also be applied to applications beyond navigation systems, as cueing directional information is a core feature of many location-based services.

Future works need to address the challenge of reducing the cognitive workload. Solutions we proposed, such as reducing the complexity of the directional information and reducing the amount of feedback should be subject of further studies. Further, all studies on tactile feedback in navigation systems studied time-limited usage only. Longitudinal studies are in order to investigate how tactile feedback performs, once the participants get acquainted to it.

## Summary and Conclusions

This chapter reports from two field experiments investigating Spatial Tactons to deliver navigation instructions. It provides evidence regarding *RQ3: Will Spatial Tactons lower the user's level of distraction?* In the first experiment, the Tactile Belt was used to indicate the location of the next and the subsequent waypoint. In the second experiment, the Tactile Compass was used to indicate the location of the next waypoint. The results of both studies show that guiding pedestrians via Spatial Tactons is effective, reasonably

efficient, and allows addressing the challenge of *distraction*. The take aways from the two studies are:

- Providing navigation instructions by Spatial Tactons cues can, in general, keep up with traditional visual interfaces. The results of the first experiment with the Tactile Belt suggests that in situations where high directional precision is required, such as at a Y-shaped crossing, the better overview provided in the map of the visual systems is still superior. Thus, as long as the road network does not get too complex, Spatial Tactons will provide a sufficient navigation performance.
- The second experiment suggests that repeating vibration patterns frequently can cause extra cognitive workload as the user focuses on the vibration, regardless whether this is needed or not. Therefore, systems employing Spatial Tactons should aim at reducing the amount of feedback as much as possible.
- Both experiments show that using Spatial Tactons allow travellers to pay more attention to the environment. The effect is stronger for the more intuitive Tactile Belt interface, which presumably caused less cognitive workload than the Tactile Compass. Thus, if supporting the user in paying attention to the environment is a crucial requirement visual interfaces should be replaced by Spatial Tactons.
- The second experiment shows that combining tactile and visual cues increases navigation performance over single modality use. Since the Tactile Compass is the less intuitive variant of investigated Spatial Tactons we assume that the same effect is true for the Tactile Belt, too. Therefore, if navigation performance, avoiding navigation errors in particular, is a crucial requirement, Spatial Tactons should be used to complement existing visual interfaces.

In summary, the studies provide evidence that Spatial Tactons can lower the traveller's level of distraction (*RQ3*). However, the results also suggest that simply replacing visual turn-by-turn instructions by tactile ones will not be sufficient in addressing *RQ4 (Efficiency): Will Spatial Tactons increase the user's navigation efficiency?* Further, the studies raised the question whether strict wayfinding is always appropriate for pedestrians. Some participants felt patronised by the tactile cues. Hence, while we have provided first proof that Spatial Tactons are beneficial in terms of distraction, the question remains how to use them so that they can be interpreted efficiently.

## 5 Increasing Efficiency of Map-Based Navigation

The results of the experiments reported in Chapter 4 suggest that Spatial Tactons can reduce the level of distraction if they are used to replace existing visual user interfaces to provide turn-by-turn instructions (*RQ3*). However, the results also confirm previous findings that turn-by-turn instructions are not necessarily the most efficient way of guidance.

In this chapter, we focus on *RQ4 (Efficiency): Will Spatial Tactons increase the user's navigation efficiency?* As starting point, we focus on the finding that many participants felt patronised and left without an overview by the turn-by-turn instructions. We therefore investigate the use of navigation based on survey knowledge as an alternative solution to route-based instructions. Survey-based knowledge is traditionally supported by maps. They provide travellers with the necessary overview so that they can choose their own routes and are, hence, not patronised. However, as pointed out in Section 1.1, maps are not the most efficient tools for pedestrian navigation. They are a flat, abstract representation of a 3D space. Hence, their content has to be mapped to the real world, which can be a complex mental process. On the other hand, the results of our experiments on turn-by-turn navigation suggest that travellers desire the overview a map provides. Also, we found that good navigation performance is correlated with a good sense of direction. We hypothesise that improving the sense of direction might also improve the efficiency of map-based navigation.

Thus, in this chapter, we investigate using Spatial Tactons to create an artificial sense of direction to increase the *efficiency* of map-based navigation. We report from two field experiments where Spatial Tactons were used to indicate the direction of the travel destination. Our results provide evidence that augmenting maps with a tactile sense of direction has a significant positive effect on the efficiency of the navigation.

### 5.1 Background and Motivation

Maps have been used for over 5000 years [HS06] to acquire spatial knowledge, orient oneself in the environment, and navigate between places. In the past, maps printed on paper were used most often. In the 21st century, technology has rapidly reshaped maps and thanks to Google brought them to our browsers and our mobile devices. The same technology has also enabled mobile turn-by-turn navigation systems, which have become standard equipment of modern cars.

Although turn-by-turn navigation systems are convenient and require less interpretation of the navigation information, paper maps have prevailed. They don't direct people along a predefined route, but allow pedestrians to choose their own routes, find shortcuts and alternative routes, help staying oriented when strolling around. As the studies in the

previous chapter have shown, people quickly feel patronised and miss the overview if only turn-by-turn instructions are provided. Hence, maps are a still viable navigation aids for pedestrians [IFIO08, RMH09]. Nevertheless, interpreting 2D paper maps and applying the inherent spatial information to the surrounding 3D environment is not a trivial task. For example, reading maps can suffer from the alignment effect [AW92], which predicts that map readers make more mistakes when not physically aligning the map with the environment.

We therefore propose to create an added sense of direction that cues the real world location of a spatial entity that is also shown in the map. We suppose that presenting the location of a reference point from the egocentric point of view helps to mentally rotate the map's geocentric content accordingly. In this work we presented the location of the destination as orientation aid, as it would be most helpful. This concept is visualised in Figure 5.1.

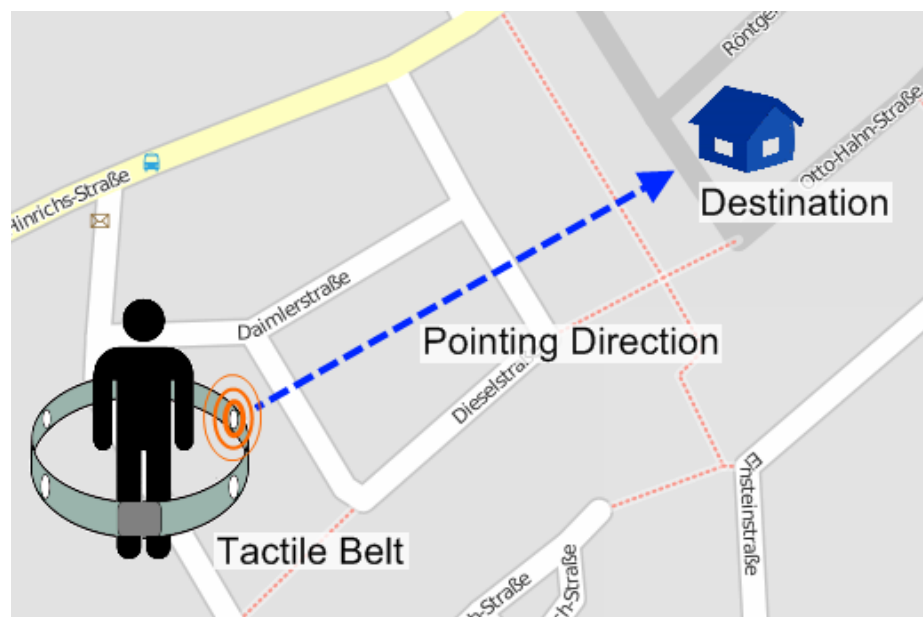


Abbildung 5.1: Cueing the direction of the travel destination with Spatial Tactons (here, using a Tactile Belt) to create an added sense of direction.

This chapter reports from two studies where Spatial Tactons are used to act as an added sense of direction. The hypothesis is that this sense of directions helps countering the alignment effect, so that navigating by map becomes more effective. The sense of direction is created by encoding the location of the travel destination, first with a Tactile Belt, second with the Tactile Compass. This chapter argues that Spatial Tactons have the potential to increase the efficiency of map-based navigation while reducing the traveller's distraction. Thus, Spatial Tactons enable a novel form of navigation cues that purely rely

on conveying directions as the crow flies and leave the actual navigation up to the inherent navigation skills of the traveller.

## 5.2 Supporting Paper Map-based Navigation with a Tactile Belt

The material in this section originally appeared in Pielot, M.; Henze, N. & Boll, S. Supporting Paper Map-based Navigation with Tactile Cues. *MobileHCI '09: Human computer interaction with mobile devices and services*, 2009

The section reports from a field study where 16 participants had to reach two different addresses with the help of a paper map. The study investigates the effects of cueing the direction of the destination as an added sense of direction with the Tactile Belt on the efficiency of applying a map to a navigation task.

The gathered evidence suggests that the added tactile cue causes people to take shorter routes, be less distracted by the map, and lose their orientation less often. Hence, the added sense of direction created by Spatial Tactons lead to a more efficient mental processing of the map's spatial information.

### 5.2.1 Creating a Sense of Direction with a Tactile Belt

In order to create an added sense of direction we used a Tactile Belt (see Fig. 5.2). Depending on the location of the tactors, stimuli can be produced all around the user. For example, a stimulus on the back near the spine is perceived as "behind" or 6 o'clock. A stimulus on the abdomen right under the navel is intuitively mapped to "front" or 12 o'clock.

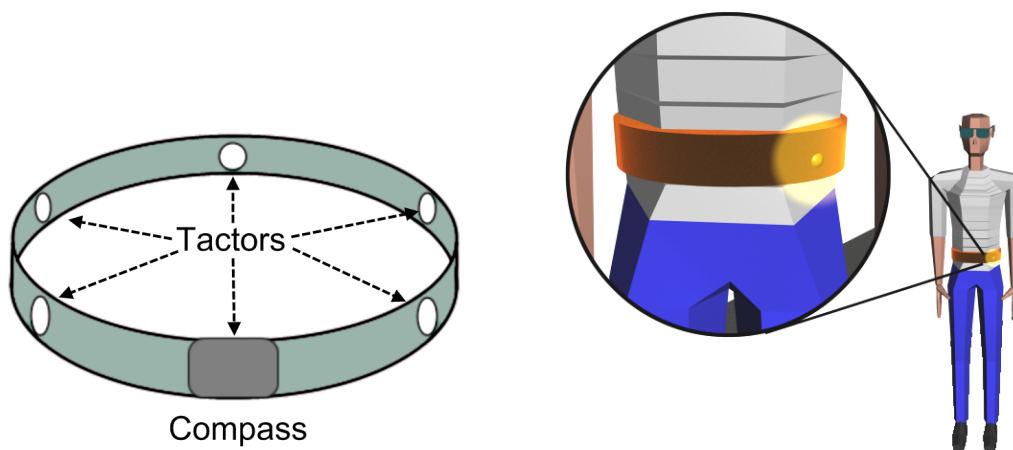


Abbildung 5.2: Sketch of the tactile belt (left), egocentric direction cueing with the tactile belt (right)



Common approaches [TY04, vVSVE04, vEvVJD05, SMMPP05] map a range of directions to single factors by activating the factor that is closest to the direction to be displayed. This limits the resolution of the devices to the number of actuators. However, as the human perception is not perfect, spatial effects of tactile perception can be exploited to generate the impression of stimuli at locations where not actuators are. Tan and Pentland [TP97], for example, utilized the sensory saltation effect. Three actuators attach along the arm in a row are activated in succession where each actuator produced three short stimuli. The user perceives each pulse in a different location, continuously wandering along the arm. However, due to the moving nature of the perceived signal this approach can not be combined with the mapping of a tactile stimulus at the waist to a horizontal direction described above. In our previous work [PHHB08] we investigated the exploitation of the apparent location effect [vE02]. This effect describes the phenomenon that two tactile stimuli are perceived as one when they occur locally close together. The perceived location of the stimulus depends on the relative magnitude of both actual stimuli. As shown in Figure 5.3, we used two adjacent factors to produce an apparent stimulus in between them. In theory, this makes it possible to produce a continuous sensation of a direction around the body.

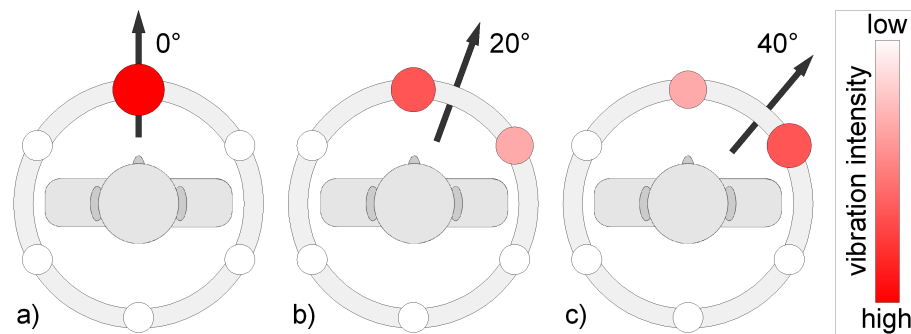


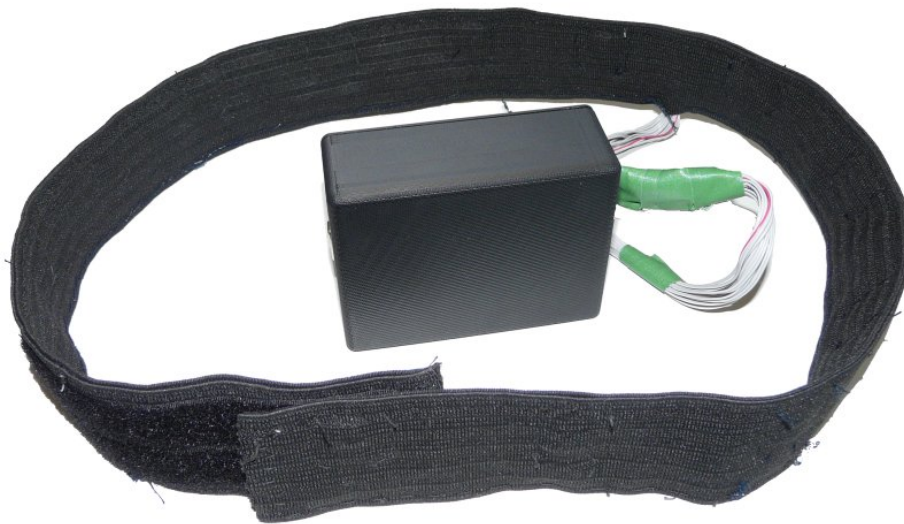
Abbildung 5.3: Visualisation of the interpolating presentation technique [PHHB08]: two actuators at 0° and 60° are used to exemplarily display three directions (0°, 20°, and 40°).

If the skin is exposed to tactile stimulation it will adapt to it, making the tactile stimulus harder to perceive [vE02]. Other researchers (e.g. [StBNL08]) therefore choose a pulsing display where the pauses between stimulations are sufficient for the skin to regenerate to full sensitiveness. However, stimulating the skin with pulses means that the stimulation is more obtrusive, as the perception constantly changes. The feelspace project [NCK<sup>+</sup>05] showed that a gentle, continuous stimulation with a tactile belt can be perceived over weeks without problems. They even showed that people started to process the directional hints subconsciously, giving people a much better awareness of their orientation and thus a better understanding of their surrounding. To mediate directions consciously we therefore decided to keep our stimulation continuous while reducing the overall intensity.

The immanent inaccuracy of today's outdoor localisation techniques, in particular the

GPS system, can result in a significant deviation between the user's real position and the measured position. The influence of this inaccuracy on the tactile output increases as the user approaches the destination. If being too close to the destination, the inconsistent position estimation could result in a confusing output. We therefore alter the display method if the user is near the destination. In order to get the user's attention we turn the display from a continuous mode into a pulsing mode. The pulses were 500ms of stimulus followed by a 500ms pause.

The hardware used comprises a custom built belt-like tactile display (see Fig.5.4). It consists of flexible fabric with six evenly distributed tactors. The used tactors have a diameter of about 11mm and can also be found in Samsung SGH A400 mobile phones. With 50% of the maximal input voltage the tactors vibrate around 100hz. The belt's control logic is integrated in a small box attached to the fabric. The box also contains an electronic compass and can be controlled by a integrated Bluetooth interface. To display



*Abbildung 5.4: The tactile belt used for the study. The flexible fabrics houses six vibrotactile actuators which equally distribute around the torso if the belt is worn.*

the destination's direction relative to the user's orientation the system must determine the user's heading and position. The integrated electronic compass provides its absolute direction in the horizontal plane. The compass has an update rate of 100Hz and an accuracy of about  $2^\circ$ . Thus, direct tactile feedback is provided if the user turns his or her body. To determine the user's position an external GPS receiver is connected to the belt. Using position and heading the direction presentation can be adjusted to the user's orientation, which enables to display absolute directions. The tactile belt is controlled by an application running on a mobile phone. This application allows specifying a geo location as destination. The belt's direction sensor and GPS receiver are used to determine the wearer's location and orientation. By comparing the user's position with the

destination's position an according vector is computed. Subtracting the direction of this vector from the user's absolute orientation leads to the direction that is displayed to the user. The distance between those two geo locations is used to determine, if the tactile stimulus is continuous (more than 50 meters) or pulsing (50 meters and less).

### 5.2.2 Method

The study took place in a village where study's participants had to reach two given destinations. The actual route to these destinations had to be chosen by the participants themselves. Therefore, they were either equipped with the paper map and the tactile belt pointing at the respective destination or with the paper map only. We assumed that the tactile directional cue would give people a better sense of orientation, which would improve the navigation with the paper map in three ways:

- **H5.1.1:** The tactile feedback will improve navigation efficiency by allowing travellers to find and take shorter routes.
- **H5.1.2:** The tactile feedback will improve navigation efficiency by allowing travellers to avoid the loss of orientation.
- **H5.1.3:** The tactile feedback will reduce the level of distraction.

#### 5.2.2.1 Environment

The evaluation took place in a typical German village with an organically grown, unsystematic street network. Besides the main roads it comprised many traffic-calmed streets and small pedestrian paths. We assigned a starting point and two destinations, so there were two different sessions planned. The first destination also served as starting point for the second session. The air-line distance between each starting point and the corresponding destination was about 500 meters. In both cases there was a long and easy route along the main roads which lead to the destinations. Additionally, there were plenty of potential shortcuts, mostly by taking smaller roads, pedestrian paths, or even open fields, such as playgrounds. Figure 5.5 shows the three places forming two sessions (get from A to B, and get from B to C). We did not provide the participants with any suggestions about what route to take. Thus, each participant had to find her or his own path to the destinations.

#### 5.2.2.2 Paper Map

As the primary navigation aid we provided the participants with paper maps that fully covered the evaluation environment. The map's size is about one square meter unfolded and the scale is 1:22500. It shows all roads and pedestrian paths in the environment. Except for the pedestrian paths all streets were labelled with the respective street name.

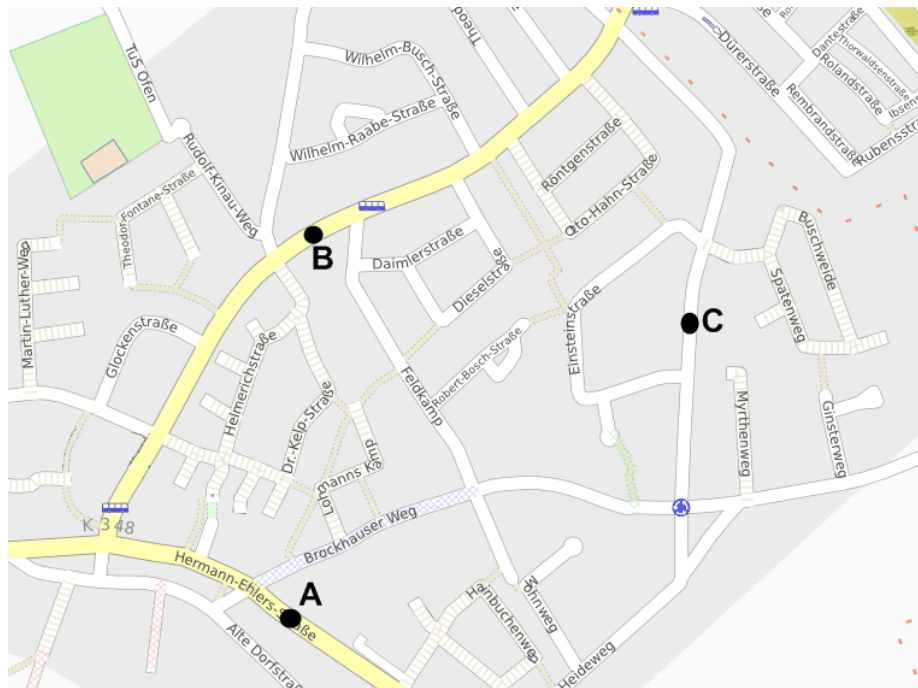


Abbildung 5.5: Overview of the evaluation environment: Participants started at **A**. Then had to reach **B** and from there go to **C** (from <http://www.openstreetmap.org/>).

The evaluation environment was printed directly onto a fold, so the map had to be at least partially unfolded to look at the whole village at once. The three places A, B, and C were marked with small dots. Figure 5.6 a participants studying the provided paper map.

During pilot studies we discovered that the maps were slightly inaccurate in some places. For example, Figure 5.7 shows a pedestrian path which is denoted as a road on the paper map. Several of these inaccuracies existed along potential routes the participants could take, so they could possibly cause the participants to loose orientation.

### 5.2.2.3 Design

In the control condition, participants received the paper map only as navigation aid. In the experimental condition we additionally provided them with the sense of direction delivered by the Tactile Belt, which was configured to point towards the session's destination. The study used a repeated-measures design. The order of conditions was counterbalanced amongst the participants. Eight participants started in the experimental condition and the other eight in the control condition. In each of these groups of eight participants gender was equally split. In order to recognise any possible sequence effects, the scores of the group that started in the control condition and the group that started in the experimental condition were checked for significant differences.



*Abbildung 5.6: The paper map that was used in the study. The evaluation environment is located near the upper-left corner of the map.*

#### 5.2.2.4 Dependent Measures

We used GPS trackers and video cameras to record the participants' movement, comments, and actions during the evaluation. The GPS trackers allowed us to reconstruct the routes each participant had walked. The video recordings allowed us to investigate the behaviour of the participants. The participants were encouraged to think aloud so their thoughts and comments were recorded on the video as well. The following dependent measures were taken:

##### Efficiency

The completion time, route length, and effective walking speed were measured as an indicator for the effectiveness of the provided navigation aids. Due to the layout of the evaluation environment, a shorter route meant that a participant had to deviate from the main roads and take side roads and pedestrian paths which were more complicated and unclear.



Abbildung 5.7: Example of the paper map's inaccuracy: a pedestrian path is shown as a street on the map (air photo from <http://maps.live.com>).

### Distraction

For quantifying how much the participants were distracted by the paper map we measured how often and how long they interacted with it. Interacting with the map was defined as people were holding the map in their field of vision.

### Disorientation

Disorientation events were defined as situations where participants stopped and either stated that they felt disoriented, or when they began to study the map and the environment for more than ten seconds while not moving into any specific direction. When participants were wearing the Tactile Belt and experienced a disorientation event, we also noted if the Tactile Belt was used to resolve the loss of orientation. We counted only those occurrences where participants explicitly stated that they based their decision about how to proceed based on the tactile cue.

### Perceived Helpfulness

After the participants had reached both destinations they were asked to rate the paper map and the Tactile Belt about how helpful they found each navigation aid for orienting themselves and how much they relied on it for choosing a route. Each of the four aspects were rated on a five-point Likert scale, where 5 corresponded to not helpful and 1 corresponded to very helpful.



### 5.2.2.5 Participants

Sixteen participants, 8 female and 8 male, took part in the user study. They were aged between 20 and 33 (Mean = 26.88). None of them was familiar with the environment where the evaluation took place.

### 5.2.2.6 Procedure

The evaluation was carried out individually. Each participants had to get from place A to place B and then from place B to place C (see Figure 5.5). Initially, the experimenter explained the relevant features of the paper map and highlighted the locations of the starting point and the two destinations to the participants. The participants also learned how different types of roads were presented on the map. Next, the participants were familiarized with the Tactile Belt and how directions were presented. Then, as training session each participant had to use a paper map and the tactile belt to navigate from the parking site to the first starting point (A). This ensured, that the participants had the chance to familiarise themselves with both navigation aids, and that they were already oriented at the beginning of both trips. Otherwise, the initial lack of orientation would have affected the results from the first route negatively. If the participants started in the control condition the belt was turned off at this point. Otherwise it was configured to display the direction of the first destination (B). The participants were then asked to find the first destination with the help of the given navigation aids. No hints about the route or the environment were given. The experimenter followed the participants with the video camera in a short distance, focussing on their interaction with the navigation aids and the environment. Once the participant reached the first destination, the conditions were switched, and the participant was asked to reach the second destination (C). Having arrived, the participants were asked to rate the map and the Tactile Belt regarding their helpfulness for orientation and navigation.

## 5.2.3 Results

The video recordings and the recorded GPS tracks were used to retrieve the qualitative and quantitative results. The videos were analysed with the help of a custom-built application. To accurately log the occurrences of predefined events and their duration, the experimenters had to press keys as long as these events occurred (see Dependent Measures 5.2.2.4 for definitions). One key had to be pressed as long as the participant observably looked at the map and another key as long as the participant observably interacted with the belt. A third key was pressed each time the participant was disoriented. In addition, the videos were used to determine each participant's travel time.

In the following the results regarding the dependent measures are given. In addition, we report unexpected significant findings related to the participants' gender. The results are visualised in diagrams showing the mean per condition and the 95% confidence in-

tervals. In the legends of the diagrams *map* denotes the results from the control condition (paper map only) and *map&belt* denotes the results from experimental condition (paper map and tactile belt). The differences are significant at a level of at least  $p < .05$  unless stated otherwise. We used two-tailed, repeated-measures t-tests to test for significant effects. In addition to the t-test results, the *r*-value are provided denoting the Pearson's correlation and thus indicating the effect size.

The repeated-measures design we used in our study is known to be vulnerable to sequence effects, such as increasing practice or fatigue, since participants repeat tasks. In order to ensure that our findings were not biased by sequence effects we checked the results from all participants first trips to all participants second trips for significant differences. Additionally, we compared the results from participants who started in the control condition with those who started in the experimental condition. These tests could not find any sequency effects.

### 5.2.3.1 Efficiency

The efficiency of the navigation aids was measured in terms of *route length*, *walking speed*, and *completion time*. The recorded GPS tracks were used to reconstruct the route that each participant had taken within Google Maps. These reconstructed routes were used to obtain the length of the travelled route without adding the variance of the GPS signal. The time needed to complete each route was taken from the videos. Route length and completion time were used to calculate the effective average walking speed for each trip. The results are given in the following paragraphs:

Figure 5.8 shows the average travelled distance per condition. The experimental manipulation caused a significant effect ( $p < .05$ ). The participants travelled longer routes in the *map & tactile* condition ( $M = 767.5, SD = 170.8$ ) than in the *map* condition ( $M = 687.1, SD = 71.0$ ). These results suggest that the tactile sense of direction caused the participants to travel shorter routes.

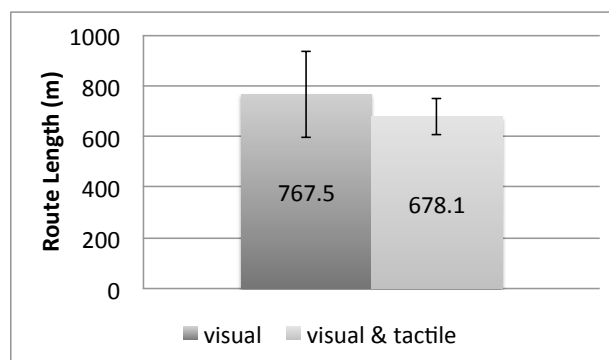


Abbildung 5.8: Route length per condition: in average, the tactile sense of direction caused the participants to take shorter routes.



Figure 5.9 shows the average walking speed (km/h) per condition. The experimental manipulation caused a significant effect ( $p < .01$ ). The participants walked slower in the *map & tactile* condition ( $M = 4.30, SD = .68$ ) than in the *map* condition ( $M = 3.86, SD = .55$ ). These results suggest that the tactile sense of direction caused the participants to walk more slowly.

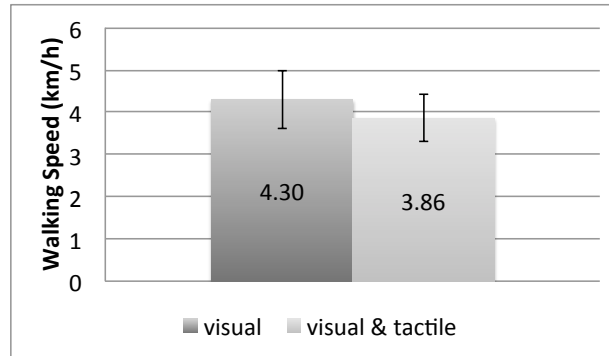


Abbildung 5.9: Walking speed per condition: in average, the tactile sense of direction caused the participants to walk slower.

Figure 5.10 shows the average completion time (min) per condition. The experimental manipulation had no significant effect ( $p = .35$ ). To reach the destination, the participants needed 10.7 minutes ( $SD = 1.6$ ) in the *map & tactile* condition and 11.0 minutes ( $SD = 3.0$ ) in the *map* condition).

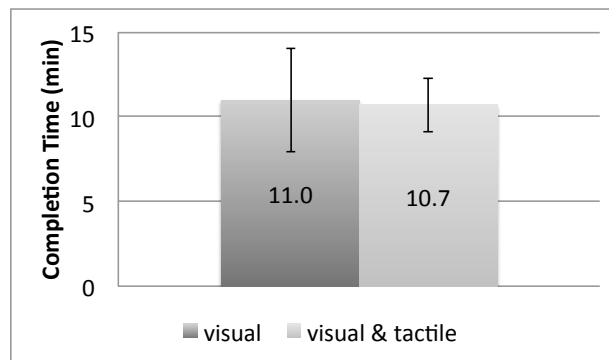


Abbildung 5.10: Completion time per condition: no significant effect on the time to reach the destination could be found.

In summary, the participants walked slower with the tactile belt but took shorter, more efficient routes, which in the end did not significantly affect the travel time.

### 5.2.3.2 Distraction

The distraction was measured in terms of how often and how long the participants checked the paper map. These measures were taken from the video recordings. We only report the average time the participants spent looking at the map, since both scores were highly correlated. The time spent looking at the map was normalized by dividing it by the completion time. The resulting values are the fractions of the travel time each participant spent looking at the map.

Figure 5.11 shows the average time (%) the participants checked the map per condition. The experimental manipulation caused a significant effect ( $p < .001$ ). The participants checked the map less often in the *map & tactile* condition ( $M = 20.2, SD = 11.5$ ) than in the *map* condition ( $M = 29.1, SD = 12.6$ ). These results suggest that the tactile sense of direction caused the participants to be less distracted.

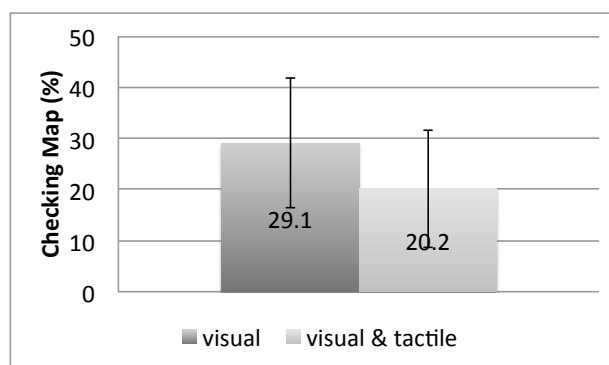


Abbildung 5.11: The tactile sense of direction caused the participants to check the map less often.

### 5.2.3.3 Disorientation

The disorientation was measured in terms of how often a participants lost her or his orientation according to the criteria outlined in Section 5.2.2.4. As the number of occurrences and the time were highly correlated we report the number of disorientation events only. The average number of disorientation events for calculated by summarizing all occurrences for each condition and divide the result by the number of participants.

Figure 5.12 shows how often, in average, the participants lost their orientation in each condition. The experimental manipulation caused a significant effect ( $p < .05$ ). There were less disorientation events per route in the *map & tactile* condition ( $M = 1.19, SD = 1.17$ ) than in the *map* condition ( $M = 1.94, SD = 2.41$ ). These results suggest that the tactile sense of direction caused the participants to be better oriented.

Furthermore, the belt often helped the participants to overcome losses of orientation.

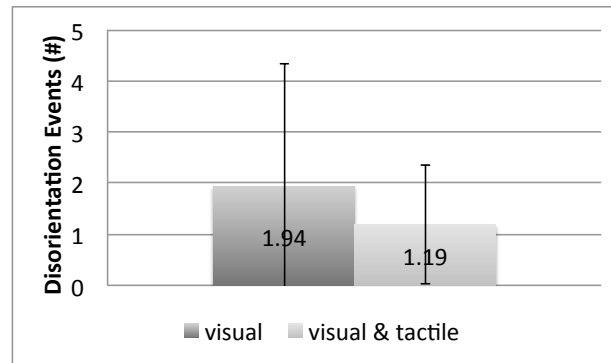


Abbildung 5.12: The tactile sense of direction caused the participants to experience less disorientation events.

In the experimental condition, in twelve out of nineteen disorientation events, participants spontaneously reported to be using the tactile belt to resolve regain orientation.

#### 5.2.3.4 Subjective Helpfulness for Wayfinding

Figure 5.13 shows how helpful the participants rated the map and the tactile belt to decide how to turn at each junction. There was a significant difference between the ratings ( $p < .01$ ). The map was perceived more helpful ( $M = 3.31, SD = .87$ ) than the tactile belt ( $M = 2.38, SD = 0.89$ ). These results suggest that the participants still relied on the map for deciding how to turn at each junction.

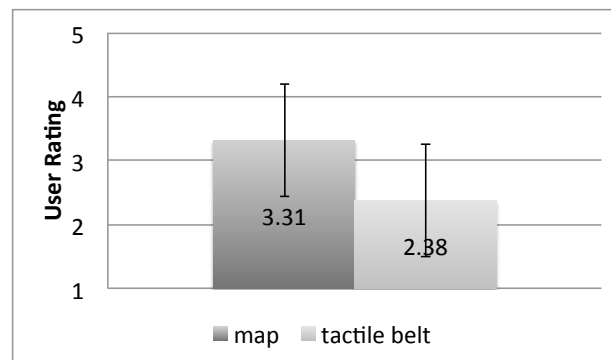


Abbildung 5.13: The map was found more helpful to decide how to turn at each junction than the tactile sense of direction.

### 5.2.3.5 Gender aspects

Besides the effects of adding the tactile belt to the paper map we also observed gender effects. Since both genders were equally represented and equally split amongst the order of conditions, we were able to analyze the data in a meaningful way.

Figure 5.14 shows how helpful the participants rated the tactile belt by gender. There was a significant difference between the female and male participants ( $p < .05$ ). Female participants rated the belt more helpful ( $M = 3.38, SD = .52$ ) than male participants ( $M = 2.63, SD = .74$ ). The results suggest that female travellers find the belt more helpful than male travellers.

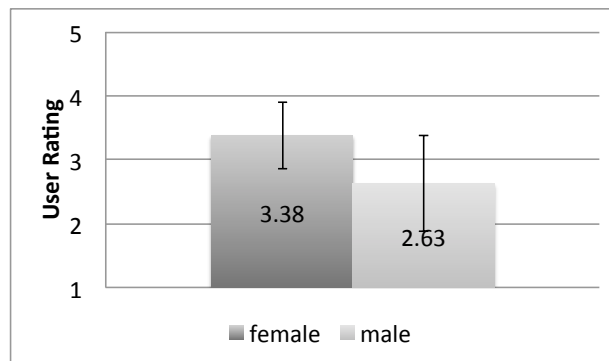


Abbildung 5.14: Female participants rated the belt to be more helpful than male participants.

Figure 5.15 shows how much time (% of route) the participants visibly used the tactile sense of direction for wayfinding and orientation by gender. There was a significant difference between the female and male participants ( $p < .001$ ). Female participants used the belt more often in a visible way ( $M = 15.55, SD = 5.14$ ) than male participants ( $M = 5.02, SD = 4.61$ ). The results suggest that female participants made more use of the tactile sense of direction.

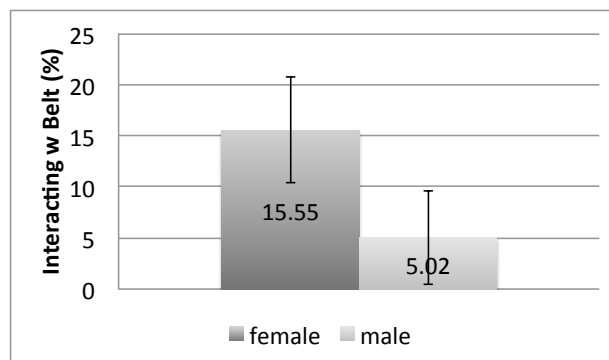


Abbildung 5.15: Female participants interacted more often visibly with the tactile belt.

### 5.2.4 Discussion

In summary, the tactile sense of direction affected the participants' navigation efficiency: they took shorter routes, spent less time studying the map, and were less often disoriented. The paper map was perceived significantly for helpful for the task of choosing the route while for maintaining a sense of orientation both navigation aids were at a par. In addition, females valued the tactile belt more helpful and used it more often than males.

**H5.1.1** (*The tactile feedback will improve navigation efficiency by allowing travellers to find and take shorter routes*) is supported by the finding that the tactile belt significantly reduced the average route length. Reducing the overall route length required the participants to move closer to the airline. Taking the main roads, however, meant accepting detours from the shortest possible route. The participants had to take smaller routes or pedestrian paths instead. Since wayfinding based on survey knowledge (e.g., the paper map) relies on being spatially oriented [RB00] the in average shorter routes indicate that the participants had a better spatial orientation when provided with the tactile cue. This also supports the findings by Smets et al. [StBNL08] where participants in a virtual world navigated more effectively with a vibrotactile directional cue of the destination. Nevertheless, the walking speed decreased significantly while the completion time was not significantly different with the Tactile Belt. We believe that people walked slower for two reasons: First, the Tactile Belt did not work perfectly well, so we had to stop in a few cases to check for potential malfunctions. Second, the participants took their time to study the tactile perception. As we did not ask them to complete the route as fast as possible, they did not feel in a hurry. Thus, we believe that a more robust device and some more familiarisation would lead to better completion times. However, we are not sure, if additional training and exercise with a Tactile Belt will reduce these kind of stops eventually.

**H5.1.2** (*The tactile feedback will improve navigation efficiency by allowing travellers to avoid the loss of orientation*) is supported by the finding that the Tactile Belt significantly reduced the number of disorientation events. Although participants mainly relied on the map for wayfinding, the belt could decrease the number of disorientation events significantly. About half of the disorientation events were caused by situations where the road network on the paper map did not correspond with the real world. This type of disorientation event was reduced stronger by the tactile belt than the other types. We therefore assume that in cases of disorientation events, where the map was not conform to the participants' expectations, the Tactile Belt reinsured them that their mental model of the environment was correct rather than the paper map. We could confirm the results from older studies about wayfinding (e.g., Ishikawa et al. [IFIO08]) that navigating with a paper map is prone to errors. In contrast to the study by Ishikawa et al. all of our participants were able to reach the destinations.

**H5.1.3** (*The tactile feedback will reduce the level of distraction*) is supported by the finding that participants looked significantly less often at the map when being equipped with the Tactile Belt. In fact, the added sense of direction seemed to replace parts of the

interaction with the paper map. In average, participants interacted roughly a quarter of the trip's time with one of the navigation aids, regardless of being at decision points or not. This supports the findings of May and Ross [MRBT03, RMT04] who analyzed route descriptions created by humans. In their studies the participants did not only describe how to proceed at decision points but also denoted landmarks between those decision points. May and Ross assume that people desire constant confirmation that their route choice was correct. The constant use of navigation aids that we observed in our study supports this assumption. While the Tactile Belt did not significantly affect the overall time that participants spend interacting with either navigation aid, replacing the use of the paper map by using the tactile belt still holds an advantage. According to Wicken's Multiple Resource Theory [Wic02] using the rarely used tactile sense for conveying information can reduce the overall cognitive load in situations with lots of visual and auditory sensations.

The participants rated the paper map significantly more helpful for choosing the route to the destination. This is not surprising, as a sense of direction will leave it up to the traveller to decide how to turn at each decision point. For maintaining a sense of orientation the ratings for the paper map's and the tactile belt's helpfulness were at a par. There was no significant preference for one of the navigation aids.

The higher appreciation of the belt by females (in terms of usage and perceived helpfulness) might indicate that an added sense of direction might support females better than males. According to Lawton [Law94] females and males tend to use different way-finding strategies. Men are more likely to use an orientation strategy: monitoring the relative location of reference points in the environment to preserve the sense of orientation. Females, in contrast, are more likely to report a route strategy: getting from one decision point to the other by following turning instructions. Thus, considering it helpful to be aware of a destination's direction and employing a route strategy, which is more likely for females, might be correlated.

### 5.2.5 Conclusions

*All roads lead do Rome!* However, the question remains how efficient we find our way. Paper maps are a common means for pedestrians to navigate towards a target destination, though people find it difficult to interpret them. In this study, we investigated creating an added sense of direction with Spatial Tactons to support the navigation with a paper map. With a Tactile Belt the direction of the target destination is displayed in addition to the map. The results from a field study show that participants navigated more effectively by taking shorter routes, they needed to study the map less often, and they lost their orientation less often. These results indicate that the participants were more confident about their route choices. They explored small side paths more often, and were less likely to lose that confidence in case of unexpected problems.

The results allow the conclusion that an added sense of direction gives the pedestrians

more confidence when navigating towards a target destination. Especially, when it becomes difficult at unclear intersection, it supports travellers in reaching a decision. Using Spatial Tactons to create this sense of direction was found beneficial, as the level of distraction decreased as well.

### 5.3 Supporting Map-based Navigation with a Tactile Compass

The material in this section originally appeared in Pielot, M.; Poppinga, B.; Heuten, W.; Schang, J. & Boll, S. A Tactile Compass for Eyes-free Pedestrian Navigation *INTERACT 2011: 13th IFIP TC13 Conference on Human-Computer Interaction*, 2011

This section reports from the experimental investigation of the Tactile Compass creating an added sense of direction. The Tactile Compass was used to continuously display the location of a destination from the user's perspective (e.g. ahead, close). In a field experiment where 14 participants had to reach a destination in a city forest three conditions were investigated: *tactile*, *visual*, and *combined*. The results provide evidence that cueing spatial locations in vibration patterns can form an effective and efficient navigation aid. Between the conditions, no significant differences in the navigation performance were found. The Tactile Compass used alone could significantly reduce the amount of distractive interaction and together with the map it improved the participants' confidence in the navigation system.

#### 5.3.1 Method

The study took place in a city forest. Fourteen participants had to reach a given destination, either by a map, by the Tactile Compass, or both navigation aids. The goals were to investigate the following hypotheses.

- **H5.2.1:** The tactile feedback will provide an effective navigation cue.
- **H5.2.2:** The tactile feedback will improve navigation efficiency when used in combination with the map.
- **H5.2.3:** The tactile feedback will reduce the level of distraction.

##### 5.3.1.1 Material

The map we provided was similar to Google Maps on current smartphones. We used a custom-built application that displays the user's position and heading on a map layer using OpenStreetMap data.

The evaluation took place in a city forest. The area offers lots of winding paths and combines dense forest with a couple of open meadows that could be used as shortcuts.

Additionally, the forest contains lots of landmarks that we used to measure how much attention the participants spent on the environment.

For the evaluation we defined three places (see Figure 5.16). The application could be configured to show one of those places on the map and display its location through the Tactile Compass. No route was displayed on the map and no turning instructions were given by the application. Thus, the participants had to find their own way to the given destination.



Abbildung 5.16: The city forest that we used as evaluation environment: the dots mark the three places we used as destination in the navigation tasks.

#### 5.3.1.2 Participants

Fourteen participants (four female) took part in the study. Their age ranged from 14 to 53 with an average of 28.25 (SD 11.51). According to the Santa Barbara Sense-of-Direction Scale (SBSOD) [HRMS02] they reported an average sense-of-direction (3.07, SD 1.14, with possible scores ranging from 1 (bad) to 5 (good)). All of the participants had little or no knowledge about the spatial layout of the evaluation environment. Since the evaluation was video-recorded the participants signed an informed consent. No payment was provided for the participation.



### 5.3.1.3 Design

The independent variable was the type of the navigation aid. To isolate effects caused by the map and by the tactile cues, we used three levels: {*map*, *tactile*, and *map & tactile*}. *Map* denoted the condition where the participants only used the map displayed on the mobile device's screen. In the *tactile* condition the device only presented direction and distance of the destination via a tactile compass. The *map & tactile* condition combined the use of the visual map and the tactile compass. We used a within-subjects design with all participants using all three navigation aids in random order. The following measures were taken in order to assess the navigation performance and distraction in each condition:

#### Navigation Performance

Similar to what has been reported in previous studies [SF07, RMH09, PHB09] on evaluations of navigation systems we measured navigation performance in terms of *completion time* and occurrences of *disorientation events*. The time the participants needed to reach the destination from the starting point of each condition was considered as completion time. Disorientation events were defined as situations where the participants stopped for more than 10 seconds, or for 5 seconds when they expressed their disorientation verbally. In addition the participants were asked to rate on a five-point Likert scale how *confident* they were with their navigation decisions. We did not measure navigation errors, since there was no "correct" route, and thus the concept of a navigation error made no sense.

#### Distraction

For measuring distraction we combined three measures. First, the participants were asked to count the *number of benches* they saw during the study. From the number of the detected and the missed benches we then computed a detection rate. Second, the participants rated how much they felt *distracted* by the device on a five-point Likert-scale. Third, we measured how long the participants *visibly interacted* with the device. Visible interaction was defined as any situation with where a participant interacts with the mobile device in a way that was visible to the experimenter. Even a mere glance at the display was considered as *interaction* as long as it was clearly perceivable by the experimenter. We divided the cumulated time of visible interaction by the completion time to get a time ratio for each condition.

### 5.3.1.4 Procedure

Prior to the study, informed consents were sent out to the potential participants. Only those participants who signed the consent forms were invited to the study. Initially, the experimenters re-explained the tasks (navigate to the given location using any path they want). The participants were introduced to the three conditions and allowed to train them.

<i>Measure/Condition</i>	<i>map</i>	<i>tactile</i>	<i>map &amp; t.</i>
<b>Navigation Performance</b>			
Completion time (s)	361.6	464.3	398.6
Disorientation ev. (#)	0.21	0.50	0.29
Confidence *	4	4	<b>5</b>
<b>Distraction</b>			
Interaction time (%) ***	35.75	<b>6.41</b>	27.82
Benches discovered (%)	46.36	50.41	41.26
Subj. Distraction	3	3	3

*Tabelle 5.1: Quantitative average results by condition. The subjective measures are the results of five-point Likert-scales, where 5 means highest. Bold faced numbers indicate that a significant effect on its condition was found.*

Prior to the first session, the participants were informed that they had to count all the benches they could find, and report the number once they had reached the destination. The places shown in Figure 5.16 had to be reached in the given order (1, 2, and 3). During the navigation task one experimenter followed the participant in some distance and recorded their action with a video camera.

Once the participants had reached a destination the completion time was noted. The participants were asked to report the number of detected benches and rate the subjective level of confidence about the navigation decisions and the subjective level of distraction for the current navigation aid. Afterwards, the condition was switched and the next place was selected as destination, until all three places had been reached. The whole procedure took about 45 minutes for each participant.

## 5.3.2 Results

All participants reached the destinations in all trials within a reasonable amount of time. No notable performance breakdown was observed in any of the conditions. In the following we report our quantitative findings as well as participant comments and our observations.

### 5.3.2.1 Quantitative Results

The quantitative results were extracted from the questionnaires and the video recordings. Table 5.1 shows the mean results for every dependent variable grouped by the condition. Statistical significance was analysed using ANOVA and Tukey post-hoc tests for the ratio variables and the Friedman Test and Benferroni corrected Wilcoxon Signed Rank tests for the questionnaire's Likert scale results.

### Navigation Performance

There was a significant effect of the navigation aid on the subjective confidence of the participants ( $\chi^2(2) = 8.45, p < .05$ ). It was significantly higher when both navigation aids were used in combination (both  $p < .01$ ). The difference between *map* and *tactile* was not statistically significant. Otherwise, no significant effects on the navigation performance were found. Neither the completion time ( $F_2 = 1.08, p = .35$ ) nor the number of disorientation events ( $F_2 = .58, p = .56$ ) differed significantly between the conditions.

### Distraction

There was a significant effect on the interaction time ( $F_2 = 15.26, p < .001$ ). A Tukey HSD post-hoc test showed that the participants interacted significantly less often with the device in the *tactile* condition compared to the *map* condition ( $p < .001$ ) and the *map & tactile* condition ( $p < .001$ ). The difference between *map* and *map & tactile* was not significant. With respect of the number of benches found, no significant effect could be observed ( $F_2 = .48, p = .62$ ). Also, the difference in the subjective distraction was not statistically significant ( $\chi^2(2) = .894, p = .64$ ).

### 5.3.2.2 Comments and Observations

#### Visible Interaction

It did not bring any value to the participants, but still we found instance of *visible interaction* in the *tactile* condition. Examples for *visible interaction* where for examples participants unlocking the screen saver (although there was nothing to see), playing with the phone's slider, or simply looking at the display.

#### Cross Country Walking

Most participants stuck to the given paths. This is surprising as the city forest contains many open areas and people are allowed to enter them. Only a few participants walked cross country. This always involved the Tactile Compass and mostly happened in the *tactile* condition. The trips where participants walked cross country were those with the fastest completion times.

#### Training Effect

Since all participants used the Tactile Compass two times, in the *tactile* condition and in the *map & tactile* condition, we could observe the learning effect in our quantitative results. They results show that in terms of navigation performance participants often performed better with the Tactile Tompass, when they used it for the second time. However, the differences were not statistically significant.

### Overview vs. Direction Cueing

Four participants stated that they had missed having an overview of the environment in the *tactile* condition. They said that the map in addition gave them an impression about further waypoints on the route, which improved their confidence. Three participants said that they preferred the combination of both navigation aids, since they cancelled out each other's weaknesses and provided the richest set of information.

### 5.3.3 Discussion

All navigation aids, the Tactile Compass, the map, and the combination of both, allowed the participants to effectively reach the given destinations. The Tactile Compass could significantly reduce the time participants interacted with the handheld device. Combining both navigation aids significantly increased the participants' subjective confidence in the system.

**H5.2.1** (*The tactile feedback will provide an effective navigation cue*) is supported by the fact that all participants reached their destination in the tactile-only condition. This goes in line with previous findings. Several studies showed that conveying general directions are sufficient to guide a traveller to a destination [MMRGS10, REJ09, RJE<sup>+</sup>10]. This paper extends the previous work by reporting the first experiment comparing this navigation technique together with and against a map. Although the participants were not familiar with the Tactile Compass and the fact that it conveys no overview, we did not find a significant disadvantage in the objective navigation performance. We carefully conclude that the Tactile Compass is not only effective but also reasonably efficient.

The results are not clear about **H5.2.2** (*The tactile feedback will improve navigation efficiency when used in combination with the map*). Previous studies show cueing the destination's direction by an egocentric tactile cue can improve the efficiency of navigating with a map [PHB09, StBNL08] (also see the previous Section 5.2). In these studies the participants were wearing a tactile waist belt pointing at the destination while navigating by a map. In both study environments, a virtual world [StBNL08] and a village [PHB09], the navigation performance significantly improved. This study could not confirm these findings, except for the improved confidence of the participants. The two relevant differences between these and the study presented here are the environments (virtual environment and village vs. forest) and the used tactile display (tactile waist belt vs. tactile rhythm patterns). The environment of the forest might have penalised bad navigation choices less than the environments from the previous work, as it allows walking cross country and the path network is very dense. Participants making a bad route choice could often correct that only shortly after. We also assume that the tactile compass is less intuitive than the very powerful waist belts. Instead of intuitive encoding of directions through body location users have to interpret the vibration patterns mentally. This may have led to performance penalties which did not occur in the above studies.

However, the Tactile Compass also showed that it may be a highly effective navigation tool when used with some training and/or in unconventional ways. Especially in the beginning some participants had difficulties to interpret the Tactile Compass, which lead to a high variance in the navigation performance measures. Since the Tactile Compass was used twice by all participants, once in the *tactile* condition and once in the *map & tactile* condition, we checked for significant differences. In fact, there is a significant increase in the navigation performance between the first use and the second use of the Tactile Compass. For example, the number of disorientation events reduce from .71 times per session (first time use) to .07 for the second usage ( $p < .05$ ). Thus, with more training we might even observe an increase navigation performance with the Tactile Compass.

Both, the highest (1162s) as well as the lowest (244s) completion times were measured for the Tactile Compass only condition. The highest completion times occurred when the participants started with the tactile compass and still had difficulties interpreting it despite the training session. This also correlated with the bulk of the disorientation events. Five out of seven disorientation events with the tactile compass occurred in only two sessions that also resulted in the two highest completion times. On the other hand, the fastest completion times were also measured in the *tactile* condition, when the participants had fewer difficulties in learning the tactile compass' vibration patterns. These users also showed a tendency to take shortcuts by walking cross-country.

**H5.2.3** (*The tactile feedback will reduce the level of distraction*) is supported by the findings. The participants were able to spot more entities they are tasked to search for [EvERD10] and pay more attention to their immediate surroundings, such as obstacles and other people [PB10b]. However, in the study presented here the participants neither felt less distracted nor spotted more benches. Again, related work [EvERD10, PB10b] studied tactile vests and waist belts, which are presumably more intuitive to interpret than the rhythm patterns of the tactile compass. We assume that the participants had to devote too much attention to the tactile cues, so the increase in cognitive workload cancelled out the advantages of the eyes-free usage. More training might reduce this disadvantage. Still, there was a positive tendency, as the participants found most benches in the *tactile* condition.

The visible distraction by the device was significantly affected by the experimental manipulation. In the *tactile* condition the participants interacted significantly less often visibly with the mobile device. At the first glance, this result might seem obvious, as there was no map to look at in the *tactile* condition. However, visible interaction was also possible in the *tactile* condition. Examples are the participants visibly listening to the tactile patterns or holding the device by the ear to "hear" the patterns. Further, the interaction with the map could have been far less, so the differences would be been insignificant. In fact, the frequent visible interaction with the map (about 28-36% in the conditions where the map was available) indicates how dangerously distracting a map can be. These findings go in line with previous studies [PHB09].

## Limitations

As every experiment, one limitation of the findings is that they are subject to Hume's problem of induction. A single experiment cannot prove that the findings will be reproduced in different settings. This means, we do not know how the tactile compass would perform in crowded Tokyo by night, a deep Finish forest in the winter, or the endless plains of the Mid West of the US.

Nevertheless, the study has shown that cueing general directions in tactile patterns – although being not necessarily intuitive – is an effective navigation aid. It showed that pedestrians can find a path to a destination in a complex, winding path network with the tactile compass only. Since most participants only used existing paths and there was mostly no line of sight between them and the destination, there is some chance that the results could be replicated in other environments with road networks as well.

### 5.3.4 Conclusions

We report from the evaluation of the Tactile Compass acting as a sense of direction that encodes the direction and distance of a travel destination in vibration patterns. We provide evidence that people can effectively navigate by vibration patterns cueing the geospatial location of a destination *as the crow flies*". This is a significant advancement of the first study reported in this chapter (5.2), where the map was always present. Here we can show that a simple directional cue can be sufficient for guiding users to a geographic location.

This opens new ways of overcoming the patronising nature of turn-by-turn instructions and the dangerous "head down" interaction caused by visual maps used on the move. This new sense allows to freely exploring the environment while maintaining oriented. It contributes to the vision of a more traditional understanding of navigation, more than going from A to B as fast as possible, rather in a sense of Kurt Tucholsky (1890-1935) stating that *Ümwege erweitern die Ortskenntnis* ("Detours expand the knowledge of a place").

Future work needs to investigate if this "tactile sense of direction" can be made more intuitive. Intuitiveness may be achieved by revising the patterns and the implicit interaction until finding the simplest but yet sufficiently powerful variant. The simpler the pattern the more beneficial the tactile compass will be in terms of distraction and cognitive workload. Further, the question of how far this concept scales has to be addressed. The presented study has shown that the tactile compass works in smaller scales of roughly a few 100 metres travel distance. We do not know how well these findings scale for longer distances (e.g. several miles) and different environments (e.g. suburbia or city centre). To support navigation at a larger scale, an approach could be to introduce intermediate landmarks to avoid walking into dead ends. However, to avoid curbing the user again, as turn-by-turn instructions do, such intermediate landmarks should be placed at

reasonable intervals, so that users "hop along a set of interesting places until reaching the destination.

## Summary and Conclusions

This chapter reports from two field experiments where Spatial Tactons were used to create a sense of direction. They provide insights into how to apply Spatial Tactons in order to address *RQ4: Will Spatial Tactons increase the user's navigation efficiency?*

In the two experiments the Tactile Belt and the Tactile Compass were used to create Spatial Tactons that constantly presented the location of the travel destination. The choice of route was left up to the traveller. The main findings from the two studies are:

- The results of the experiment with the Tactile Compass suggest that indicating the direction of the travel destination using Spatial Tactons can already be sufficient to guide travellers there. Thus, if reaching the destination as fast as possible is not a requirement, indicating its direction as the crow flies is a sufficient form of navigation support.
- Both experiments show that creating a sense of direction via Spatial Tactons has significant positive effects on the efficiency of map-based navigation. The Tactile Belt caused the travellers to take shorter routes and lose orientation less often. The Tactile Compass increased the subjective trust into the navigation system. Therefore, if map-based navigation is a requirements, such as when the overview the map provides is needed, the navigation efficiency can be increased by adding a sense of direction using Spatial Tactons.
- In the case of the Tactile Belt, the experiment suggests that adding a sense of direction via Spatial Tactons can reduce how often and long travellers check the map and, hence, can reduce the traveller's level of distraction. Thus, if reducing the level of distraction is required, it may not be necessary to replace the map, as it would be for turn-by-turn navigation systems.
- The results support the previous findings from the two experiments on turn-by-turn navigation that combining tactile and visual cues again increases navigation performance over single modality use. Hence, complementing visual interfaces with Spatial Tactons can help increasing the navigation performance if that is required.

Both studies showed that the idea of cueing the direction as the crow flies" was well received and turned out to be surprisingly effective. In contrast to turn-by-turn navigation, participants did not feel patronised. In the experiment on the Tactile Compass that took place in a city forest we even observed that users feel encouraged to stray away from the given paths and start walking cross country. We also argue that in some cases maps might even not be needed and that Spatial Tactons provide a sense of direction about

the location of a place that allows users to reach it without further navigation assistance. Hence, using Spatial Tactons to cue directions "as the crow flies" has shown to be a viable answer to *RQ4: Will Spatial Tactons increase the user's navigation efficiency?*





## 6 Improving Perception of Spatial Information

The results of the experiments reported in the previous chapters 4 and 5 suggest that Spatial Tactons can successfully address the challenges of *distraction (RQ3)* and *efficiency (RQ4)*. However, it is not yet clear to what extent they address *RQ5: Can Spatial Tactons be perceived despite high perceptual and cognitive load?* In all four studies the perception of information provided by visual user interfaces was degraded by such interferences, such as sunlight or the need to watch out for other people in a crowded street. Nevertheless, the degradation did not become significant enough to render visual user interfaces unusable. Therefore, in this chapter we will investigate, to what extent Spatial Tactons can deliver spatial information in situations with serious interferences of the user's perception. In two experiments we deliver spatial information that is crucial to the users' situation awareness via Spatial Tactons. We investigate how well they can perceive and process this information compared to when it is delivered via visual user interfaces. Our results suggest that users maintain better situation awareness when the relevant information is conveying via Spatial Tactons. Thus, Spatial Tactons allow users to maintain situation awareness in situations where eyes and ears suffer from too much input.

### 6.1 Background and Motivation

In our daily life we oftentimes rely on situation awareness, which involves "the perception of elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"[End95]. For example, when crossing a road we spot cars, determine their driving vector, and only pass the road if it is clear. We employ our senses to perceive what is going on around us interpret the signals and make decisions. Important entities for our perception of the environment are the location, direction and distance of places and possibly moving objects and persons. This information contributes to our decision to wait at the crossing, to turn right to reach a point of interest, or just follow our friends through the city centre.

However, the environment may not be suitable to the perception capabilities. A simple example of impaired perception is if it is impossible to read a device's display because of sunlight reflections. However, some environments are even more challenging. Consider going out with your friends visiting a large music festival (see Fig: 6.1): you and your friends stroll around on the festival ground but darkness, the crowd, and noise make it very difficult to stay together. In stressful environments like these, perception and interpretation might be impaired, which consequently degrades the situation awareness. The emitting signals of the environment simply do not match the free resources for our perceiving of the environment. It is too dark to see well, too loud to hear well, too busy to continuously focus on the group [PHB08]. At the same time, perceptual resources are

still free and can be used to perceive the information over a different sensory channel, the sense of touch.



*Abbildung 6.1: A crowded festival is a good example of a demanding environment, with a lot of sensory interferences, including darkness, artificial lights, chatting, and loud music.*

As argued in Section 1.2 previous research suggests that providing information by the sense of touch can improve the cognitive processing of that information while reducing the probability of a cognitive overload in such situations [Wic84].

This chapter reports from two studies where Spatial Tactons are used in situations with high perceptual and cognitive load. In both studies they are used to keep track of people in a demanding environment. The chapter will argue that Spatial Tactons are well perceived despite high perceptual and cognitive workload and lead to an improved situation awareness. Thus, even at a festival with its loud music, the dense crowd of people, and blinding artificial light, Spatial Tactons enable us to keep track of spatial entities, such as our friends.

## **6.2 Where is my Team? Supporting Situation Awareness with a Tactile Belt**

The material in this section originally appeared in Pielot, M.; Krull, O. & Boll, S. Where is my Team? Supporting Situation Awareness with Tactile Displays. *CHI '10: SIGCHI conference on Human factors in computing systems*, 2010

This study investigates to improve situation awareness about moving objects, such as friends, by displaying their location via the Tactile Belt. Therefore, we employed the technique developed in Chapter 3.1. The aim was to study the effectiveness of this information presentation in a demanding situation. Embedded in a 3D multiplayer team game the Tactile Belt, thus, was used to convey the locations of the team members. In a lab experiment we compared the performance and situation awareness of teams with and without added tactile information presentation. The results provide evidence that the locations of the team members cued by the Tactile Belt were well perceived and processed and lead to a significant improvement of the team's situation awareness.

### 6.2.1 Background and Motivation

Situation awareness (SA) is a term that first came up in the avionics and was used to describe how well a person understands a situation. It involves the perception of the elements in the environment, the comprehension of their meaning, and the projection of their status in the near future [End95]. In the case of the initially presented scenarios (e.g. visiting a crowded, noisy festival with your friends) this definition could refer to knowing where the friends are, understanding what they are doing, and predict where they will be in a few minutes.

Situation awareness is formed in three steps: perception, comprehension, projection. Perceiving the relevant elements in the environment is the first step and leads to level 1 SA. In the comprehension step, the isolated knowledge about the relevant elements' states will be joined into a comprehensive picture of the current situation. The final step is the projection of the state of the observed elements in the near future and leads to level 3 SA. The higher the level of SA becomes the more effective one can react to the environmental state.

Since these steps build on top of each other, subsequent steps are dependent on the previous one. If the initial perception of the relevant elements in the environment fails the subsequent comprehension and projection steps are not possible. Consequently, for a good SA a sufficient perception of the environment and the comprehension of the perceived elements are crucial. For a user interface this allows to conclude that we should support a good perception of the elements relevant for situation awareness while leaving sufficient attentional resources to process that information in steps two and three.

The presented approach aims at improving situation awareness for groups of people by visualizing the location of the group members with a tactile display. In this section we embed our work in the related work in the field. To formalize the problem we address and provide a theoretical framework by reviewing theories regarding situation awareness and cognitive workload. We elaborate how the understanding of a situation, respectively knowing the location of people, can be improved by using the sense of touch as information carrier. A review of the related work on displaying spatial information with tactile displays presents existing approaches to encode and visualize information in spatial displays and shows how this relates to our approach.

### 6.2.2 Evaluation Environment

In order to evaluate the effectiveness of presenting the location of people on the situation awareness we needed to deploy it in a situation where knowing the location of other people is a highly relevant element of the situation awareness. In addition, we were seeking a usage context that generates a high load on the auditory and visual senses, so improving perception and processing of information becomes a significant factor.

Inspired by recent studies [SMMPP05, StBNL08] we favoured a virtual environment over a field study, since the lab situation allows better measurement and the results would be less affected by unsystematic variance. As evaluation environment we chose a well-known 3D multiplayer game called Counter-Strike. In this game each player controls a virtual avatar from a first-person perspective, i.e. the player sees through the eyes of the virtual person. The players are organised in two teams that have conflicting goals and compete in preventing the other team from reaching them. Via network or internet people can populate those teams and join via different PCs. The game generates a high cognitive load on the player. The game is fast-paced. Players need to concentrate on the current situation and need to react quickly to a wealth of auditory and visual stimuli. At the same time, if the team advances according to a previously agreed plan, it is important to track the location of each team member.

The game play is separated into rounds. Each round, both teams try to score by reaching their respective goals. After each round, the game state is reset and both teams are put back into their starting locations. For this work we used game type called *defuse*, where one team has to place a explosive charge at a specific place while the other team needs to prevent this or defuse the charge in time. This scenario was chosen, as good team play is most effective here. The members of the charge-laying team can try to distract and sneak around the defending team. The members of the defending team need to be sure that all possible routes are monitored.

A system called TactileCS was developed to display the positions of the team members via the tactile belt. It consists of a plug-in for Counter-Strike servers using the AMX mod<sup>1</sup> which distributes the locations of the players through a UDP port. On the tactile belt's side a component written in C# was used to receive and process the player locations transmitted via the UDP port. The component provides a graphical user interface where the player can adjust how the locations are presented with the tactile belt.

The location of the team members were encoded by the method presented as result of Chapter 3.1. Since one of our findings was that all three tested Tacton parameters, namely duration, intensity, and rhythm, allow to encode the spatial distances effectively, TactileCS allows choosing one of these distance encodings. Players can further alter the "loudness" of the tactile signal, choose the number of distance classes, and alter the speed of the serial presentation of directions. We allowed this degree of freedom to see if common usage patterns emerge over time, such as the preference of one of the two parameters for encoding distances.

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<sup>1</sup> <http://amxmod.net/>

### 6.2.3 Method

The goal of this study was to show whether the tactile position display is effective in high cognitive workload situations and where knowing the location of the individuals of a group is important for the situation awareness. Our hypotheses were that:

- **H6.1.1:** The perception of relevant information bits (level 1 SA) improves.
- **H6.1.2:** The comprehension of the situation (level 2 SA) improves.
- **H6.1.3:** The collaboration between the team members (level 3 SA) improves.

#### 6.2.3.1 Participants

Fourteen participants took part in two different sessions. Their age ranged from 25 to 30 with an average of 27. They were recruited from the university environment. All of them were familiar with computers and first-person games.

#### 6.2.3.2 Material

Each participant was provided with a notebook where an instance of the game was installed. A network switch was used to create a local area network between the notebooks. On half of the notebooks we additionally installed our TactileCS software that was used to control the tactile belts' output. To each of these notebooks a tactile belt was connected via serial cable or Bluetooth.

#### 6.2.3.3 Design

The availability of the tactile location presentation served as independent variable. In the experimental condition all members of a team were equipped with tactile belts. In the control condition, none of the team members were wearing a tactile belt. We used a repeated-measures design, so each participant contributed to both conditions. To cancel out sequence effects, half of the participants would use the belt initially while the other half would use it in the second part of the study. Following the categorisation by Salmon et al. [SSWG06], the situation awareness was measured by subjective self-judgement, judgement by external observers, and objective performance-based measures.

For the subjective self-judgement we used the Situation Awareness Rating Technique in form of the SART-3 questionnaire [End98, SSWG06]. Participants had to reflect their situation awareness for each round in the game. The SART-3 asked the participants to rate (1) the *demand* of attentional resources, (2) the *supply* of attentional resources, and (3) the *understanding* of the situation. While more complex SART questionnaires exist, we chose this scaled down variant to not overburden the participants with the need to answer too much questions each round. In addition to the SART-3 questions, the participants had to rate their subjective impression of how well the team play went in the past

round. All judgements were expressed through five-point Likert scales, where 1 would mean bad and 5 would refer to good situation awareness or team play.

The external judgement of the situation awareness was conducted by the Situation Present Assessment Method (SPAM) [DD04]. In this method, an external person, such as the experimenter, interrupts the participants in the middle of the task to probe the participants understanding of the current situation. In the presented study, the experimenters asked the participants to describe the current situation and judge how well the own team progresses. The experimenters rated on five-point Likert scales how *fast* and *accurate* the response was and how *certain* the participants made their judgements.

The objective performance measurement was based on how often and in which way the round was won or lost. A team can win a round by throwing out all players of the other team or by deploying the explosive charge at a given spot, respectively denying that. We counted how often a team won the round. Statistics of individual players were ignored, since those scores are mostly based on the skill of the player and thus are less likely to be influence by situation awareness.

In addition, the quality of the team play was assessed by self-reports and external observations. Every participant and both observers rated the team play of their team after each game round. Again, team play was rated on a 5-point Likert-scale where 5 denoted very good team play.

#### 6.2.3.4 Procedure

The study took place on two evenings. Each evening the participants were divided into two equal sized groups. The two groups were split up to sit on the opposite sides of a broad table so they were facing each other. Each group always joined the same in-game team. Each members of the group on one side of the table as equipped with a Tactile Belt.

Every round comprised three phases: (1) filling out the SART-3 questions for the past round, (2) agreeing on a plan, (3) and executing the plan while possibly having to explain the situation to the experimenter. In order to allow the participants to familiarise themselves with this procedure the evaluation started with an open training session. The participants learned how to use a printout of the virtual environment to silently agree on a plan by announcing it through the team chat of the game. They trained to stick with that plan and keep track of their team mates. During this training phase the experimenters already conducted SPAM questioning, so the participants could get used to being interrupted during the game and describing the situation. The participants also learned to judge the subjective situation awareness by the SART-3 questions. The training session was continued until the participants had internalised the procedures. This took about 90 minutes.

During the evaluation session 32 rounds were played in four different setups: each group played both game teams twice, once equipped with tactile belts and once without.

Table 6.1 shows the four resulting constellations. When the belts were switched to the other group after round 16 we there was a short break for regeneration and to give the experimenters time to adjust the belts to their new wearers. Between round 16 and 17 another training session was conducted to give the teams the time to adjust to the new situation with or without the tactile belts. Since most of the procedure was already known, this second training session was shorter.

<b>Rounds</b>	<b>Group 1</b>	<b>Group 2</b>
1-8	Belt & Team 1	No Belt & Team 2
9-16	Belt & Team 2	No Belt & Team 1
17-24	No Belt & Team 2	Belt & Team 1
25-32	No Belt & Team 1	Belt & Team 2

*Tabelle 6.1: Segmentation of the 32 rounds*

We closed the experiment by an open discussion where the participants were asked to elaborate their experience with the tactile belt, how they used it, and what differences there were between using and not using the tactile belt.

#### 6.2.4 Results

Unless specified otherwise, all results were tested for significant effects using a two-sided, repeated-measures t-test. As there were some problems in the pilot session regarding responding to SPAM questions, lack of team play, and technical problems, the quantitative results are only reflecting the second session. We therefore analysed 192 subjective ratings (with 4 scores each), 64 external ratings (also with 4 scores each), and 32 performance measures.

##### 6.2.4.1 SART-3 (Subjective SA Assessment)

The state of attentional resources was assessed by analysing the items *demand of attentional resources*, *supply of attentional resources*, and *understanding of the situation* from the SART-3 questionnaire. The demand of attentional resources referred to the question of how much effort the participants had to devote to keeping track of their team mates. The supply of attentional resources referred to how well they could keep track of the team mates' locations thanks to the additional cues. Understanding of the situation referred to how well the participants understood the current situation. Each item was rated on a 5-point Likert-scale where 5 meant least demand and best supply of attentional resources.

Figure 6.2 shows the subjective rating of the *demand of attentional resources*. There was a significant effect of the tactile location presentation ( $p < .001$ ). The participants felt less demand on the attentional resources in the experimental condition



( $M = 2.14, SD = .95$ ) than in the control condition ( $M = 2.98, SD = .96$ ). These results suggest that the tactile location presentation lowered the demand of attentional resources.

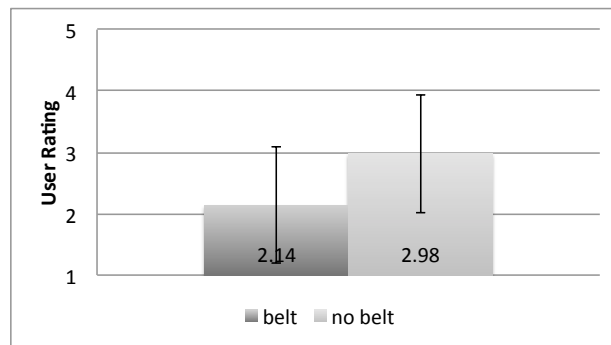


Abbildung 6.2: The subjective ratings of the demand of attentional resources per condition. The tactile location presentation significantly lowered the demand of attentional resources.

Figure 6.3 shows the subjective rating of the *supply of attentional resources*. There was a significant effect of the tactile location presentation ( $p < .001$ ). The participants felt a better level of supply in the experimental condition ( $M = 3.00, SD = .95$ ) than in the control condition ( $M = 2.34, SD = .99$ ). These results suggest that the tactile location presentation improved the supply of attentional resources.

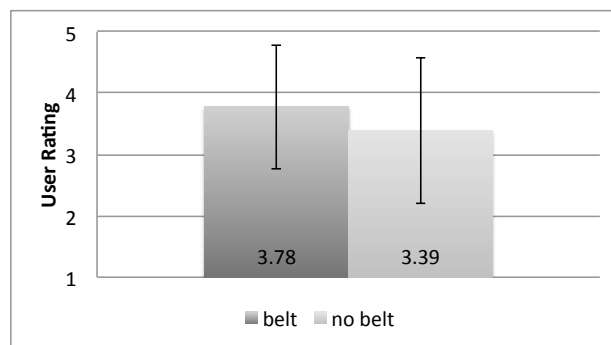


Abbildung 6.3: The subjective ratings of the supply of attentional resources per condition. The tactile location presentation significantly improved the supply of attentional resources.

Figure 6.4 shows the subjective rating of the *understanding of the situation*. There was a significant effect of the tactile location presentation ( $p < .05$ ). The participants had a better subjective understanding of the situation in the experimental condition ( $M = 3.78, SD = 1.01$ ) than in the control condition ( $M = 3.39, SD = 1.18$ ). These results suggest that the tactile location presentation improved the understanding of the situation.

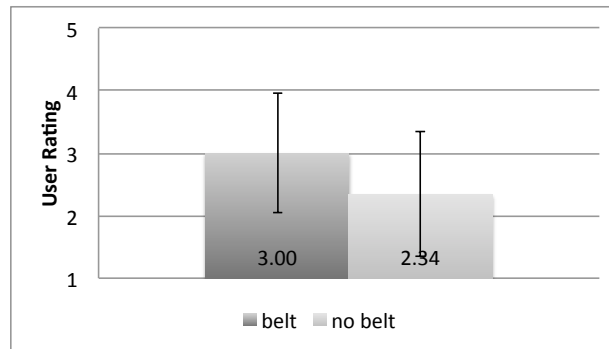


Abbildung 6.4: The subjective ratings of the understanding of the situation per condition. The tactile location presentation significantly improved the understanding of the situation.

#### 6.2.4.2 SPAM (External SA Assessment)

Regarding the SPAM probing the situation awareness was quantified by how prompt, accurate, and certain the participants answered the question how the game was progressing with respect to the initial plan. Certainty, accuracy, and promptness were rated on a 5-point Likert-scale where 5 denoted the highest level of situation awareness.

Figure 6.5 shows the experimenters' ratings of the *accuracy* of the SPAM response. There was a significant effect of the tactile location presentation ( $p < .01$ ). The participants' responses were more accurate in the experimental condition ( $M = 4.22, SD = .97$ ) than in the control condition ( $M = 3.53, SD = 1.14$ ). These results suggest that the tactile location presentation made it easier for the participants to describe the current situation accurately.

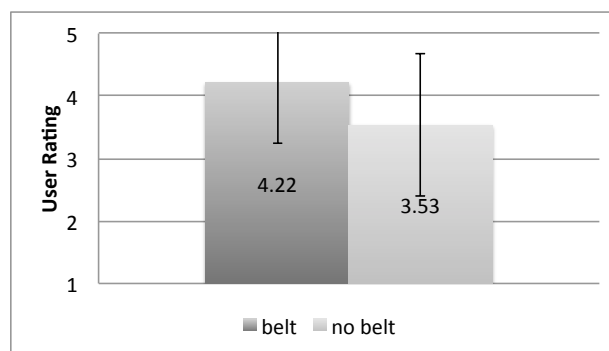


Abbildung 6.5: The experimenters' ratings of the accuracy of the SPAM responses per condition. The tactile location presentation significantly increased how accurate the participants responded to the experimenters interruption.

Figure 6.6 shows the experimenters' ratings of the *speed* of the SPAM response. There was a significant effect of the tactile location presentation ( $p < .05$ ). The participants

responded faster in the experimental condition ( $M = 4.50, SD = .72$ ) than in the control condition ( $M = 4.00, SD = .95$ ). These results suggest that the tactile location presentation made it easier for the participants to describe the current situation quickly.

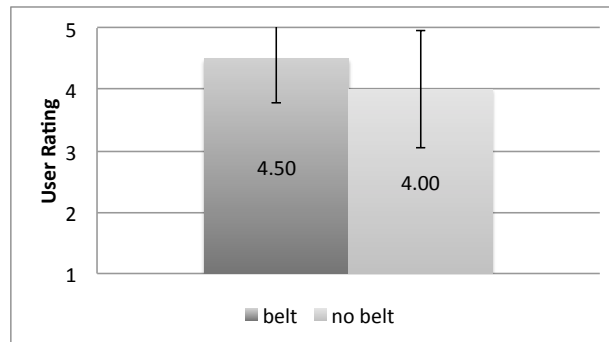


Abbildung 6.6: The experimenters' ratings of the speed of the SPAM responses per condition. The tactile location presentation significantly increased how fast the participants responded to the experimenters interruption.

Figure 6.7 shows the experimenters' ratings of the *certainty* of the SPAM response. There was a significant effect of the tactile location presentation ( $p < .05$ ). The experimenters rated the certainty higher in the experimental condition ( $M = 4.50, SD = .72$ ) than in the control condition ( $M = 4.00, SD = .95$ ). These results suggest that the tactile location presentation made participants more certain about their assessment of the situation

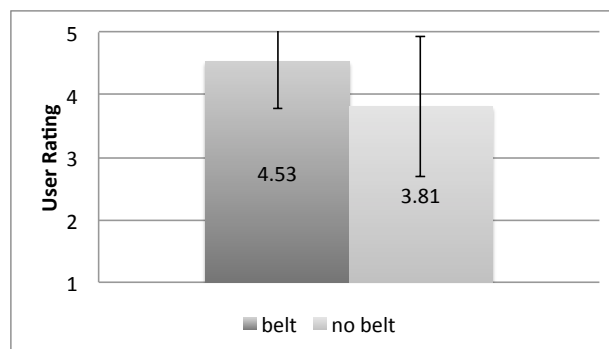


Abbildung 6.7: The experimenters' ratings of the certainty of the SPAM responses per condition. The tactile location presentation significantly increased how certain the participants responded to the experimenters interruption.

#### 6.2.4.3 Objective Performance

Nineteen of the 32 rounds were won by the team that was equipped with the tactile belt. However, the difference turned out not to be significant (CHI-square test,  $p = .13$ ).

How successful the team was in laying the charge (or defusing it respectively) was also not affected by the belt. Both success rates were nearly equal in both cases between the experimental and the control condition.

#### 6.2.4.4 Team play

Figure 6.8 shows the participants' ratings of the team play. There was a significant effect of the tactile location presentation ( $p < .001$ ). The participants rated their team play better in the experimental condition ( $M = 3.89, SD = .89$ ) than in the control condition ( $M = 3.56, SD = 1.07$ ). These results suggest that for the participants the team play appeared to improve with the tactile location presentation.

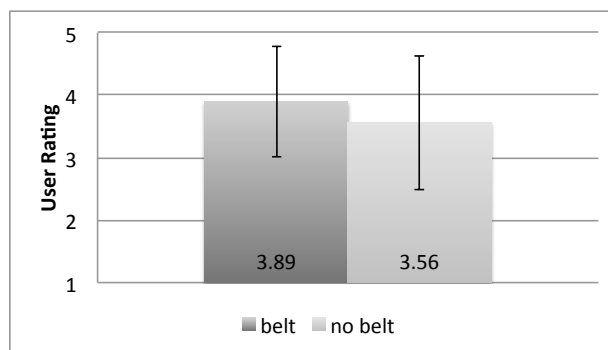


Abbildung 6.8: The participants' ratings of the team play per condition. The tactile location presentation significantly improved the participants' subjective rating of the team play.

Figure 6.9 shows the experimenters' ratings of the team play. There was a significant effect of the tactile location presentation ( $p < .001$ ). The participants rated their team play better in the experimental condition ( $M = 4.53, SD = .67$ ) than in the control condition ( $M = 3.66, SD = 1.12$ ). These results suggest that for the experimenters the team play appeared to improve with the tactile location presentation.

#### 6.2.4.5 Comments and Observations

At the end of each session, we conducted an open discussion with the participants about their experiences with and without the tactile position display. The participants felt that using the tactile position display did not distract them from perceiving other important things from the virtual environment. Two participants explained that using the tactile belt gives a sense of well-being: feeling the positions of the team members in the right direction indicates that the situation is under control. It was also reported that the tactile pulses were processed without being explicitly noted after a while. The external observers found that when using the tactile position display the individuals of a team spread further out, whereas without the system the team stayed closer together.

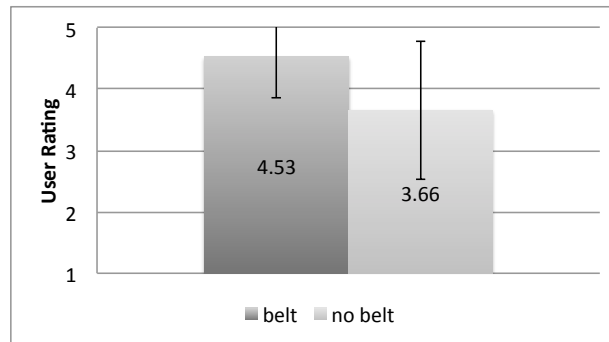


Abbildung 6.9: The experimenters' ratings of the team play per condition. The tactile location presentation significantly improved the experimenters' subjective rating of the team play.

### 6.2.5 Discussion

The evaluation results show that displaying the team mates' locations has significant positive effects on the situation awareness and the team play. The participants reported an increase in attentional resources and a better understanding of the situation. According to the external judges, the participants were able to express current situations faster, more accurate, and with higher certainty. Team play improved according to the self-perception of the participants and the judgements of the experimenters. The objective performance improved but not at a significant level.

**H6.1.1** (*The perception of relevant information bits (level 1 SA) improves*) is supported by the study results. The significantly lower perceived demand of attentional resources confirms the prediction of the Multiple Resource Theory [Wic84]. Since we conveyed information by the tactile modality, which otherwise was not used for information presentation, the overall cognitive load reduced. The participants' comments further support this finding as the tactile position display was found to be intuitive and not distracting from the game play. Our findings also go conform to the results reported by Duistermaat et al. [DEvER07] where a tactile navigation aid lead to a better perception of the environment compared to two visual navigation aids. Drawing on these results we believe that the tactile position display improved the perception of elements that are relevant for situation awareness (the location of the team member in our case) and therefore lead to a better level 1 situation awareness.

**H6.1.2** (*The comprehension of the situation (level 2 SA) improves*) is supported by the study results, too. Both, the SART-3 questionnaire as well as the SPAM probing indicated significantly increased situation awareness for the team with the tactile position display. According to the SART-3 responses the participants felt better supplied with relevant information and had subjectively improved situation awareness. In addition, they were able to better describe their current situation to the experimenter. Altogether

these findings indicate a better comprehension of the situation with the tactile position display.

**H6.1.3** (*The collaboration between the team members (level 3 SA) improves*) is partially supported by the study results. Regarding the qualitative results the participants reported an improved feeling of having the situation under control. The need to communicate verbally also reduced. In addition, the collaboration seemed more efficient as the individuals spread further out with the tactile position display. The performance measures recorded nineteen wins versus thirteen losses with tactile position display, however, the number of wins was not different at a significant level. In the case of the presented study, other factors, in particular how good participants were in playing the game, seemed to have a larger impact on team performance.

On the basis of these findings, we can conclude that despite high cognitive and sensory workload, participants could effectively process the locations of the team mates presented by Spatial Tactons. Since H6.1.1 and H6.1.2 are both supported the tactile position display must have been effective in improving the perception and comprehension of the team mates' locations. This means that the tactile position display had a positive effect on mediating the relevant information bits to the user. According to Endley's situation awareness model [EBJ03] important factors for gaining situation awareness are interface design, stress & workload, and complexity. Drawing on the Multiple Resource Theory we infer that reducing the cognitive workload was one of the causes for the improved situation awareness. Again, this supports the findings by Duistermaat et al. where a tactile navigation display allowed for the best perception of the environment.

## 6.2.6 Conclusions

In this study we investigated the effect of presenting the location of team members in a virtual 3D game on the situation awareness of the team. A comparative experiment showed that the players have increased situation awareness when being equipped with Tactile Belts. These results show that the presented spatial information was *perceived* despite high perceptual and cognitive workload.

To be able to generalise our findings beyond the game we based our work on two scientific theories: Endley's situation awareness model, which predicts that getting a good SA is impaired by high cognitive load, and Wickens' Multiple Resource Theory, which predicts that the overall cognitive load will not much increase if information is present through an *idle* sense. In combination both theories predict that conveying relevant information with a tactile display leads to a better SA when eyes and ears are "busy", as in the presented experiment. The presented study can be seen as a falsification attempt to the combination of the two theories. The results we found support the theories' predictions. Since those theories claim to be valid for any situation, not only the 3D multiplayer game, we can hypothesize that the same effect can be observed in different

situations, e.g. when visiting a crowded festival. However, more falsification attempts are needed before we can trust our findings to be general.

### 6.3 Keeping Groups Together with a Tactile Compass

The material in this section originally appeared in Pielot, M.; Poppinga, B.; Heuten, W.; & Boll, S. A Tactile Friend Sense for Keeping Groups Together. *CHI EA '11 Proceedings of the 29th of the international conference extended abstracts on Human factors in computing systems*, 2011

#### 6.3.1 Introduction

When visiting festivals with a large number of friends, one of the challenges is keeping the group together. Having to look out for the others is challenging given the crowded and noisy nature of such events. The bigger the group is the more stress is induced in meeting up [Col01]. In our previous work [PHB08] studying groups visiting festivals, we encountered several events where people got lost for the rest of the evening. We found that the common approach to locate the group or lost individuals is to use the mobile phone and agree to meet at a common landmark. However, as found in our previous studies, the noise at typical festivals makes it difficult to talk on the phone. Also, it is hard to agree on a landmark. Only the location of few landmarks, such as the ferris wheel, are known or visible to everyone. However, the typical night-out-mood can make it difficult to convince all individuals of a group to move to such a landmark to pick up a lost person.

Commercial services, such as Google Latitude or Yahoo Fireeagle, address this challenge by allowing users to publish their own location through their mobile phone so others can see it on a map. However, many leisure events take place at night and often the venue is quite crowded. Thus, interacting with tiny screens will force the user to shift attention between the screen and the environment to avoid walking into obstacles [AVB05]. The sense of touch is largely unaffected by such environmental interferences. It has been shown that tactile feedback is sufficient to support rendezvousing of groups [WRS<sup>+</sup>10] and can act as a sixth sense [NCK<sup>+</sup>05]. We therefore investigated the feasibility of using tactile feedback as a sense of a friend's location to support groups in staying together during at a festival.

Extending our previous work [PHB08] we designed and implemented a vibro-tactile user interface that cues the geospatial locations in vibration patterns. We integrated it into FriendSense, a mobile application that allows sharing one's location. The application was tested with groups visiting one of the biggest festivals in Germany with about 1.5 Million visitors each year (see Figure 6.10).



Abbildung 6.10: The Kramermarkt festival in Oldenburg, Germany, where the field study took place

### 6.3.2 Design Space of a Nightly Companion

We aim at creating a connection between friends, but at the same time do not spoil the experience of the nightly event. Thus, we had to address the questions of how to describe the location of a friend and which sensory modalities should transport that description so that the result is suited for a nightly companion?

#### 6.3.2.1 Describing Locations

A common approach for describing one's location is relating it to a landmark, e.g. "I am next to the ferris wheel". Such information can be described easily on the phone. The disadvantage is that both sides must have a shared knowledge about the landmarks. This can be difficult, since people visit festivals infrequently and their layout probably change over time. Another approach is conveying locations geocentrically by a map. The advantage is that it is not necessary to have shared knowledge about the landmarks. However, reading a map is not trivial for everyone, as it requires mapping its 2D content to the real world. This becomes even more difficult if the map does not show the layout of the festival environment. Another option is describing locations from an egocentric perspective, e.g. by using its relative direction and distance (e.g. 2 o'clock in 200m). The advantage with such descriptions is that they neither require mapping them to existing geographic



features nor require shared knowledge about the environment. In the ever-changing environment of a festival such descriptions are the most robust form of communicated geospatial locations.

### 6.3.2.2 Suitable Sensory Modalities

The nature of a festival (noisy, crowded, and nighttime) also raises the question of the actual sensory modalities used for the information presentation. The information presentation should be robust against noise. The need to look at a display should be reduced as much as possible, since looking at a display while navigating through a crowd is highly demanding and it may increase the likeliness to bump into another person [AVB05]. Finally, as nightly events are often used to maintain social contacts, the information presentation should be unobtrusive and not hamper the user's visual appearance (e.g. by requiring to wear head-mounted displays). These requirements exclude most modalities and traditional interaction techniques. Auditory feedback is impracticable due to the expected noise level. The use of visual feedback is possible, but only if it is sufficient to consume it in short and infrequent glances. There must be no need to look at the display when e.g. moving through the crowd or chatting with another person. This leaves us with the sense of touch, as it is hardly affected by darkness and noise. It can be used to convey information in an unobtrusive way that remains invisible to others and may interfere less with social interactions.

### 6.3.3 FriendSense

In our previous we therefore proposed an application called FriendSense [PHB08]. However, the previous design was based on tactile waist belts, which are difficult to provide in sufficient numbers to actually deploy the system. Thus, we created a version of the application that only requires common smart phones. Via 3G networks the user's GPS location is regularly shared with a server. Once retrieved, the location is relayed to the other connected FriendSense clients. Thus, every FriendSense client is aware of each friend's location all the time. Each FriendSense user is able to consume a friend's shared location through visual or vibro-tactile feedback.

#### 6.3.3.1 Visual Feedback

The visual component of the FriendSense consists of a radar-like user interface (see Figure 6.11). It shows the direction and the distance of all online friends via small dots. The UI is kept as simple as possible to reduce the time needed to read its state. It aligns itself with the user's heading, so the directions can be read directly from the screen without rotating them mentally. The user can use this UI to select the friend that shall be presented through the sense of touch.



Abbildung 6.11: Screenshot of the visual component of FriendSense: direction and distance of all friends are shown in a radar-like UI. In the illustrated situation, two friends have strayed away from the group, which is to the left-hand side. The red dashed line indicates which friend the user has selected to be displayed via the tactile feedback.

### 6.3.3.2 Vibro-tactile Feedback

To present the location of the selected friend, we used the Tactile Compass as presented in Section 3.2.4 (see Fig. 3.9). For example, two short pulses indicate that the friend is straight ahead. A long pulse followed by a shorter pulse, as shown in Figure 3, indicates that the friend is to the left-hand side. As shown in the study that is reported in Section 3.2.4, the recognition rate was 78%. That result is sufficient for the intended use. First, more errors were off by one sector to the left or right, so the general tendency was mostly recognized correctly. Second, the patterns are played repeatedly as long as a friend is selected, so it is not fatal if the user is temporarily a bit off the mark. The distance is encoded in the pause between the patterns. The closer the friend is the faster the patterns are repeated.

To avoid annoying the user we muted the tactile feedback when not moving. First, groups often stay in one place for a while. In these situations, constant vibration feedback would be only disturbing. Second, users who are searching for the group or lost individuals are either on the move or they can stop to take a glance at the visual radar interface.

### 6.3.4 Method

To get first feedback on FriendSense we deployed the application in groups of friends visiting a nightly festival. We wanted to investigate

- **H6.2.1:** The perception of the location of the friends (level 1 SA) improves.
- **H6.2.2:** The comprehension of the where one's friends are (level 2 SA) improves.
- **H6.2.3:** The group will show improved interaction (level 3 SA).

#### 6.3.4.1 Participants

On two different nights a total of 12 participants took part in the study. The two groups consisted of friends that were visiting the festival as a leisure activity. The participation in the study was secondary to them.

#### 6.3.4.2 Design

To study the effect of the location cueing techniques we used a between groups design with two conditions: participants in the experimental group were equipped with the fully functional FriendSense. The participants in the control group received stripped down version which only shared its location but did not display the others' locations in any form. The location was shared to ensure that the participants from the experimental group could sense all members of the group.

As means of data-collection we used the experience sampling method (ESM) [CW03] and post-hoc interviews. In our ESM implementation the application triggered an alarm every 20 minutes. Then, a short questionnaire consisting of five-point Likert scales appeared on the device's screen. The participants had to rate how relaxed they felt [Relaxation], how much attention they spent to keep the group together [Attention], and how difficult they perceived it to keep the group together [Difficulty]. Further, we asked whether the participant was with the main group. If the answer was "no" we also asked if the participant had left the group on purpose or not. The results were stored on the device together with a timestamp.

#### 6.3.4.3 Procedure

All participants were introduced to the application some days before the actual study, so they already knew how to operate and use it. On the night of the study, the experimenter met the group of friends at the beginning of their visit outside the festival area. The group then visited the festival as they normally would. The post-hoc interview was conducted the day after. We asked open questions on how FriendSense had been used, how possible separations from the group were experienced, and how FriendSense affected the general experience of the event.

### 6.3.5 Results

On the first evening, one person came late. Later on, two people split up from the group for about an hour. On the beginning of the second evening some people split up from the group in the beginning to join it again 20 minutes later. Later that evening, a single person left the group two times. Thus, most of the time the group stayed together, or was split into two parts.

The vibration, in general, was hard to perceive when the phone is left in the pocket. First, the general level of activity (moving, talking, ...) decreases the sensitivity to vibration. Second, since it was cold, most participants wore jackets and kept the phones on the jacket pockets. The clothings are typically too thick for the vibration to be perceived anymore. Hence, the strategy of most participants was to keep the phone on the hand or rest a hand on the jacket pocket when they wanted to perceive the vibration.

In the following, the collected quantitative data is analysed. All variables were tested for significant effects using a two-sided, independent-measures t-test.

Figure 6.12 shows how relaxed the participants felt. There was a significant effect of the tactile friends sense ( $p < .05$ ). The participants felt more relaxed in the experimental condition ( $M = 3.36, SD = 1.41$ ) than in the control condition ( $M = 2.77, SD = 1.09$ ). These results suggest that the tactile friend sense made caused the participants to relax.

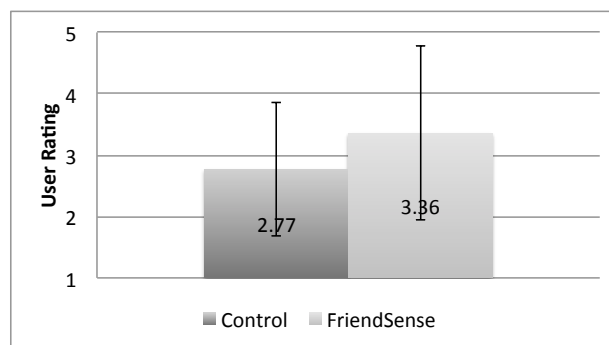


Abbildung 6.12: The participants' ESM ratings of how relaxed they feel per condition. The tactile friend sense significantly increased how relaxed the participants felt.

Figure 6.13 shows how much attention the participants felt they had to devote to keeping the group together. There was a significant effect of the tactile friends sense ( $p < .05$ ). The participants had to devote less attention in the experimental condition ( $M = 1.17, SD = .54$ ) than in the control condition ( $M = 1.86, SD = 1.06$ ). These results suggest that the tactile friend sense made it easier for the participants to keep track of the other members of the group.

Figure 6.14 shows how difficult the participants found it to keep the group together. There was a significant effect of the tactile friends sense ( $p < .05$ ). The participants

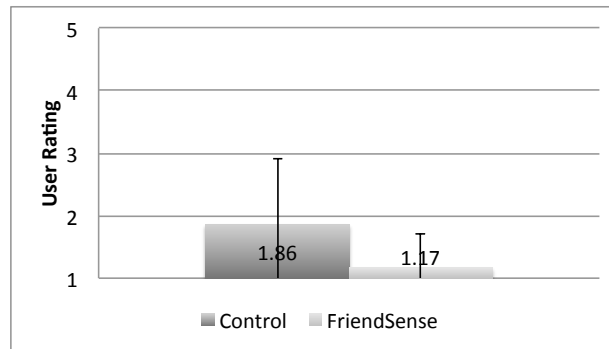


Abbildung 6.13: The participants' ESM ratings of how the level of attention devote to the location of the others per condition. The tactile friend sense significantly subjectively decreased the necessary level of attention.

found it less difficult in the experimental condition ( $M = 1.29, SD = .81$ ) than in the control condition ( $M = 1.71, SD = 1.13$ ). These results suggest that the tactile friend sense made it subjectively less difficult to keep the group together.

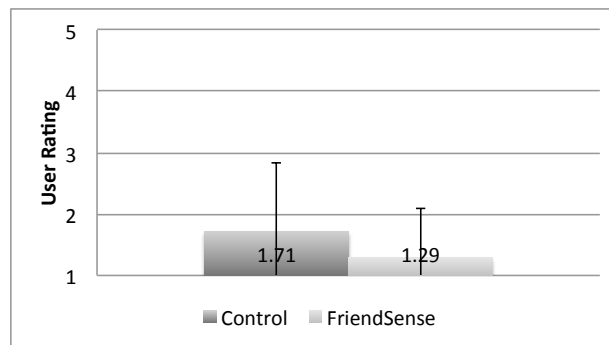


Abbildung 6.14: The participants' ESM ratings of how difficult the found keeping the group together per condition. The tactile friend sense significantly lowered the subjective difficulty.

The participants from the experimental group reported six occasions of not being with the group, but always intentionally. The participants from the control group reported ten occasions of not being with the group. In three cases this was intentional, in seven it was by accident. The difference was not statistically significant.

### 6.3.5.1 Interview Results

From the post-hoc interview we learned that the participants subjectively did not use the system much. The most important feature of FriendSense was considered the ability to be located by the group if necessary. Thus, being separated from the group was not considered as fatal as it would have been without the system. This was even true for the

participants in the control group. Since they shared their location as well the participants from the experimental group could still locate them. Some participants even felt encouraged to leave the group, knowing that the others could find them. The tactile feedback was appreciated when moving through the very crowded areas of the festival area. The participants acknowledged that in contrast to the visual display it was suited well for being used on the move and in the crowd.

### 6.3.6 Discussion

The results show that with the tactile FriendSense, participants were more relaxed, paid less attention to where their friends are, and found it less difficult to keep the group together. In addition, none of the participants from the experimental group (using FriendSense) reported to have gotten lost unintentionally.

**H6.2.1** (*The perception of the location of the friends (level 1 SA) improves*) and **H6.2.2** (*The comprehension of the where one's friends are (level 2 SA) improves*) are supported by these findings, as the participants were more aware about their friends' whereabouts.

**H6.2.3** (*The group will show improved interaction (level 3 SA)*) cannot fully be supported. Though, in the control condition, participants got lost unintentionally, the numbers are not statistically significant, so we cannot rule out unsystematic variance as explanation.

One of the study's limitations is that the participants from the experimental group could track those from the control group. This had the effect that the control group participants were more confident as they could be found if they got lost. Thus, the difference between using FriendSense and using no technical device at all might be even more significant.

### 6.3.7 Conclusions and Future Work

In this study, the Tactile Compass worked well in a festival environment and improved the experience of the night out. In particular, it made the participants more confident not to get lost and thus had a positive effect on the user experience. The work shows that continuous tactile cueing of coarse information accompanied by a visual overview that can easily be read is suited to such chaotic environments. In particular the tactile feedback - although comprising a rather non-intuitive set of patterns - could effectively be put to use in this casual scenario. The future work needs to focus more closely on the information presentation itself. Remaining questions are how the tactile feedback can be extended to communicate a wider range of information, e.g. several friends' location at the same time.

## Summary and Conclusions

This chapter reports from two experiments where Spatial Tactons were used to provide users a sense of the location of their team mates / friends. The goal was to investigate if Spatial Tactons are reliably *perceived* (RQ5) in situations with a lot of perceptual and cognitive workload. In the first experiment the Tactile Belt was used to display the user the location of up to three team mates in a virtual 3D environment. In the second experiment the Tactile Compass was used to keep the visitor of a crowded festival informed about the location of the group. The take aways from the two studies are

- The studies reported in this chapter show that the presence of Spatial Tactons has measurable effects on most of the dependent variables. This means that the participants were able to perceive and to process them, despite the high perceptual and cognitive workload. Therefore, if spatial information needs to be communicated in such situations, Spatial Tactons provide a viable means to do so.
- The first experiment has shown that the rather complex serial pattern used to display the location of multiple entities with the Tactile Belt was sufficiently intuitive. Despite the constant cognitive demand of the primary task the participants had a significantly better idea of what was going on. Thus, Spatial Tactons can be used to improve situation awareness in cognitively demanding situations.
- The results from the second experiment suggest that the adding Spatial Tactons can have positive effects of the mood on people at leisure time who are afraid of getting lost or losing sight of their group. Hence, if it is desired to keep people calm and confident and/or to provide a good user experience, Spatial Tactons can create a virtual bond between people.

Both studies provided positive answers to RQ5: *Can Spatial Tactons be perceived despite high perceptual and cognitive load?* Furthermore, the feeling of understanding where one's friends or mates are was highly appreciated by the participants. Similar to the Sixth Sense approach by Nagel et al. [NCK<sup>+</sup>05], Spatial Tactons can create a new for the location of objects, which at the same time remains reasonably unobtrusive.

## 7 Conclusions

This chapter concludes the thesis. It summarises the presented work, highlights the contributions to the field & discusses their limitations, provides hints to designers on how to use Spatial Tactons in practice, and outlines future work.

### 7.1 Contributions

The thesis contributes to our scientific knowledge by proposing and evaluating Spatial Tactons, i.e. novel ways of encoding spatial information with vibro-tactile displays. Six experiments provide evidence that Spatial Tactons, applied to different real-world scenarios, can effectively address the challenges of distraction, efficiency, and perception. This section summarises these contributions.

#### 7.1.1 Spatial Information and Tactile Displays

**RQ1 (Fundamentals): What is the state of the art in encoding spatial information in tactile user interfaces?** is addressed in Chapter 2. On the basis of previous research on how humans mentally organize spatial information, we argue that conveying the location of landmarks from an egocentric perspective by encoding their distance and direction in relation to the user is the most suitable approach in the context of this thesis. Reviewing previous research on presenting information via tactile user interfaces in general, and spatial information specifically, we argue that the most intuitive approach is encoding spatial directions via the location of a tactile stimulus on the body. Beyond, we identified that the *intensity* of a vibration stimulus, its *duration*, and creating different *rhythm* patterns are additional ways suitable to encode information in the targeted context. We conclude that related work lacks two aspects: it does not answer how to encode direction and distance of multiple spatial entities. Further, there is little investigation to what extent the other parameters (rhythm, duration, intensity) can be used to convey spatial information, when, for example, the goal is to use a mobile phone’s vibration motor as tactile displays.

#### 7.1.2 Spatial Tactons

**RQ2 (Spatial Tactons): How can spatial information be encoded by tactile user interfaces?** is addressed by Chapter 3. We propose the term *Spatial Tactons* to describe abstract tactile messages that encode the direction and the distance of spatial entities. Reviewing the fundamentals of the mental representation of spatial information and encoding information in tactile displays, we argued that Spatial Tactons should aim at presenting direction and distance of spatial entities from an egocentric perspective (e.g.



"11 o' clock, 200m"). Previous work has proposed encoding direction in body location using tactile vests, belts, or arrays.

Advancing previous work, we proposed serial presentation of entities, and experimental proved that this is a feasible approach. In contrast to previously proposed parallel presentation, this allows to encode additional information (e.g. spatial distance or other characteristics) for each entity in rather simple ways. Different parameters for encoding distance have been proposed by previous work. This thesis provides the first systematic investigation of the potential parameters (rhythm, intensity, duration) and their experimental comparison. All of the parameters allowed encoding distance, though none of them turned out to be particularly intuitive. With the rhythm-based encoding, participants were best at judging spatial distance. Concept and details of this study are published as part of [PKB10].

Also, we present the first systematic investigation into how to encode spatial information without using multi-actuator displays. We found that the concept of mapping vibration patterns to directions, although complicated, is a reasonable approach. It is also compatible with encoding spatial distance in duration. We proposed the term Tactile Compass for this design. In a study with 21 participants, 78.19% (SD 14.61) of the directions encoded by the Tactile Compass we recognised correctly, showing that the approach is reasonably effective. Concept and study are published as part of [PPS<sup>+</sup>11].

### 7.1.3 Distraction

**RQ3 (Distraction): Will Spatial Tactons lower the user's level of distraction?** is addressed in Chapter 4). In order to study whether Spatial Tactons can lower the user's level of distraction, we tested Spatial Tactons for providing navigation instructions in two field experiments.

In the first experiment, we used the tactile belt to convey the location of the two upcoming waypoints of a route. A commercial (pedestrian) navigation system with visual user interface served as baseline. The study took place in the crowded city centre of Oldenburg, where bumping into other people or obstacles is not unlikely if the traveller does not pay enough attention to the environment. We found significant effects on the navigation performance and the level of distraction. With the tactile belt, the participants made more navigation errors, but experience less near-accidents. Experiment and findings are reported as part of [PB10b].

In the second experiment, we used the Tactile Compass to convey the location of the next waypoint of a route. This experiment had three conditions: the Tactile Compass, a visual navigation system, and the combination of both. Without visual feedback, travellers interacted less with the handheld device. The combination of visual feedback and Tactile Compass reduced the number of navigation errors. The presence of tactile feed-

back, however, led to slower walking speeds, which might be explained by increased cognitive load. Experiment and findings are reported as part of [PPHB11].

The results of the field experiments show consistently that Spatial Tactons help to reduce *head down* interaction, i.e. instead of watching their surroundings, users keep the screen of the handheld device in their focus, which results into decreased awareness about their environment. One experiment sending the participants through a very crowded city centre showed that the reduced head-down interaction leads to less near accidents. In the first experiment, we could even reduce the amount of head-down interaction without taking the visual interface away. However, in the two experiments with the Tactile Compass, the reduction of head-down interaction was not significant enough to lead to measurable consequences. In these experiments, we failed to show that people pay more attention to objects in their environment. One explanation might be the increased cognitive workload that we encountered in one of the Tactile Compass experiments. The advantages of freeing eyes and ears from perceptual workload might be mitigated by this added cognitive workload. Nevertheless, we also found significant training effects. The longer people used the Tactile Compass, the better they performed with it. Thus, cognitive load might decrease over time. Altogether we conclude that both interfaces, tactile belts and the Tactile Compass, allow travellers to pay more attention to the environment.

#### 7.1.4 Efficiency

**RQ4 (Efficiency): Will Spatial Tactons increase the user's navigation efficiency?** is addressed by Chapter 5. While the two studies above showed that Spatial Tactons which deliver turn-by-turn navigations instructions lower the traveller's level of distraction, the participants also felt that the lack of an overview of route, such as found in maps, make them feel patronised. Maps provide an overview of a geographic area, but the 2D representation required to mentally align its content to the environment, which can be inefficient for navigation tasks. In two field experiments, we investigated the use of Spatial Tactons to provide a tactile *sense of direction* to improve the efficiency of navigating by the help of a map.

In the first experiment, we used the tactile belt to create a tactile sense of direction by constantly presenting the location of the travel destination. Participants were equipped with a paper map and were asked to reach a given destination. The presence of the tactile feedback had significant effects on the efficiency of the map-based navigation: the participants took shorter routes, checked the map less often, and lost their orientation less often. Experiment and findings are reported as part of [PHB09].

In the second experiment, we created a tactile sense of direction with the Tactile Compass and experimentally tested it against and together with a map on a handheld device. When using the Tactile Compass only, participants interacted significantly less with the device. The combination of both navigation aids significantly improved the participants'

subjective trust in the navigation aid. Experiment and findings are reported as part of [PPS<sup>+</sup>11].

The results from the experiments show that Spatial Tactons can create an effective and efficient sense of direction. Unlike visual displays, Spatial Tactons can continuously convey location information without distracting the user from the environment and the primary task (e.g. the navigation itself). Additionally, we have shown that the location of one or several fixed or moving spatial entities can serve as orientation points. The two experiments where we augmented maps with a tactile sense of direction allowed users to apply map-based spatial information more efficiently to the navigation task. The second of these two experiments also showed that a tactile sense of direction only conveying the location of the travel destination can be sufficient to guide a user there. The two final experiments showed that Spatial Tactons can measurably improve the situation awareness, which indicates that the spatial information was provided in a form that could efficiently be processed to create an understanding of the situation. Altogether, this shows that interpreting spatial information presented from an egocentric perspective (direction and distance) leads to very efficient spatial displays. It enhances the efficiency of interpreting other source of spatial information, such as maps.

#### 7.1.5 Perception

**RQ5 (Perception): Can Spatial Tactons be perceived despite high perceptual and cognitive load?** is addressed by Chapter 6. It reports from two experiments, where we used Spatial Tactons to create a sense of direction. However, this time with the aim of improving the users' situation awareness in situations with perceptual interferences.

In the first experiment, we used the tactile belt to continuously keep the user informed about the location of three team mates in a multiplayer game. We found significant effects of the presence of the tactile sense of direction. Using standard measures to quantify the teams' situation awareness, we found that teams had a better understanding of the situation when each member was equipped with a tactile belt. Experiment and findings are reported as part of [PKB10].

In the second experiment, we took groups to a crowded and noisy festival and used the Tactile Compass as a *friend sense*, i.e. a user interface that continuously conveys the location of a friend. Users could select one of their friends and the Tactile Compass then continuously presented the location of that friend. The presence of the tactile friend sense had significant effects on the participants' mood. Using the Experience Sampling Method, we found that friend-sense users felt more relaxed and found it less difficult to keep the group together. Experiment and findings are reported as part of [PPB11].

These results show that the perception of Spatial Tactons is not suffering from situation-induced impairments, which we typically encounter in situations where location-based services are used. In both experiments, the participants were subjected to high percep-

tual and cognitive workload. Still, the participants were able to perceive and interpret the Spatial Tactons, which led to significant improvements of the understanding of the situation.

### 7.1.6 Conclusions

The aim of the thesis was to study how to present spatial information to users of location-based services in suitable ways. On the basis of theories of human information processing, we have argued that three challenges may arise when interacting with mobile devices outdoors and on the move:

1. If spending too much attention on the handheld device, users may become *distracted* from the environment, which can be dangerous if it happens in e.g. traffic.
2. The form in which the spatial information is presented may limit its *efficiency* when applied to a task, such as finding one's way through unfamiliar terrain.
3. The *perception* of the information that the device emits may be hampered by external interferences, such as noise or sunlight reflections.

The results from above experiments provide evidence that Spatial Tactons have the potential to help tools that are designed to provide situation awareness or navigation support to overcome these challenges.

## 7.2 Limitations

This section discusses the limitations of the presented approach, the used research methods, and the results presented in this thesis.

A general limitation to experiments, as used in this thesis, is that they are subject to Hume's problem of induction. For example, we cannot assume that all swans are white just because all swans we have observed so far are white. In the context of Spatial Tactons, this means that a single experiment, which shows that they can reduce the user's level of distraction, does not necessarily prove that all types of Spatial Tactons will lower its user's distraction in all kinds of situations. Consequently, we cannot be sure how the Tactile Compass would perform in crowded Tokyo by night, a deep Finish forest in winter, or the endless plains of the Mid West of the US. Nevertheless, all of the experiments presented in this thesis provide evidence that Spatial Tactons can convey spatial information that can be applied effectively and efficiently to real world tasks. Also, we derived our approach from Wickens' Multiple Resource Theory [Wic84]. Unlike experiments, scientific theories offer a set of principles that explain and predict phenomena and claim to be generally valid within the constraints they define. The experiments reported in this thesis can be seen as a falsification attempt in the sense of Karl Popper's philosophy of

Falsifiability. As the experiments have shown that Spatial Tactons can be perceived despite high perceptual workload, and that they lower the user's level of distraction, their results corroborate the Multiple Resource Theory. They provide evidence that the theory is applicable to interacting with location-based services and tactile user interfaces, too.

The Spatial Tactons presented in this thesis and the results drawn from the six experiments are all based on two types of tactile displays: a single actuator display (Tactile Compass) and a multi-actuator display in the shape of a belt. However, other approaches of conveying directional information via tactile displays have been proposed. For example, Tan and Pentland [TP97] proposed using an  $n \times n$  array of actuators to draw lines and shapes on the wearer's back. We also investigated conveying spatial information via two actuators, one for each hand [PPHB12b]. Nevertheless, for the given scenario of providing spatial information in the horizontal plane, tactile belts are the only display type to present directional information in relation to the human's egocentre. Using e.g. an  $n \times n$  array would require to mentally rotate the lines drawn on the back to the horizontal plane. A study by Srikulwong and O'Neill [SO10] provides evidence that such arrays are less intuitive than tactile belts. On the other hand, we have presented three experiments featuring the probably most unintuitive type of interface: a single actuator. Unlike other forms of multi-actuator displays, extracting a direction encoding with a single actuators will involve mental workload. Thus, the findings of the six experiments comprise a very intuitive and a very demanding tactile interface. The intuitiveness of other interfaces proposed in the past will probably be situated between these two extremes. Thus, findings that occur in both tactile displays will probably apply to other interfaces, such as tactile arrays, too.

Throughout the experiments presented in this paper, the baseline to which Spatial Tactons are compared to varies. The four experiments on Spatial Tactons for navigation used two different navigation systems, a digital map, and a paper map. The two experiments on the perception of Spatial Tactons compare to visual radar-like visualisations of locations. For each of the experiment, a baseline (navigation system, map, radar) was chosen that resembles state-of-the-art support for the given task. By not using the exact same navigation system, map, radar, it becomes more difficult to compare the results between the pairs of experiments (distraction, efficiency, perception). However, due to the variety of studied systems, the findings can be generalised further, as they do not only apply to a single baseline.

All results in this paper are based on participants who were inexperienced with Spatial Tactons. Although we had, sometimes extensive, training sessions in all experiments, we found that our participants still improved over time. The most salient occurrence of such training effects can be found in Section that reports from the field experiment on using the Tactile Compass to enhance the traveller's sense of direction. Since there was a *tactile* condition and a *combined*, each participant used the Tactile Compass twice, once with a map and once on its own. Comparing the first use of the Tactile Compass with its second use, we found significant increases in the usage performance. These findings suggest that

with increasing experience, Spatial Tactons might become more effective and efficient. At the same time, all of the participants had at least little experience with the baselines we used, such as maps and navigation systems. Thus, if Spatial Tactons are employed in systems that are regularly used, their advantages in relation to these baselines might even become more distinct.

## 7.3 Applying Spatial Tactons

This section elaborates in which contexts Spatial Tactons can be useful and how they should be applied.

### 7.3.1 Which display to use?

This thesis has investigated two types of tactile displays to create Spatial Tactons: multi-actuator displays (tactile belt), and vibration patterns created with an ordinary smartphone (Tactile Compass). Related work [REJ09] has recently proposed a third viable alternative for smartphones, namely pointing gestures with non-visual feedback.

Throughout the six experiments the tactile belt had the stronger positive effects. Thus, if there is a necessity to reduce the level of distraction or ensure the constant perception of spatial information multi-actuators displays should be preferred. The disadvantage of such displays are that they are not ready to use and will rather be found in areas first, where the need of reducing the level of distraction justifies the necessary technology and maintenance (e.g. pilots, rescue squads, ...).

If the casual user is addressed, pointing gestures or vibration patterns can be sufficient. Pointing gestures are far more intuitive but also require potentially fatiguing or socially inappropriate pointing gestures. The vibration pattern approach is to be preferred when the phone shall be kept in the pocket, such as when the user desires to not stand out, or if both hands are needed elsewhere, such as when the user is riding a bicycle. In one experiment we tested the combination of both approaches and found that they can mitigate each other's weaknesses.

### 7.3.2 Tactile or Multimodal Feedback?

This thesis has investigated using Spatial Tactons to replace and to augment existing visual user interfaces. The results consistently show that replacing visual interfaces leads to less distraction. Augmenting existing interfaces leads to better performances. Thus, if reducing the amount of head down interaction is the goal, designers should go for replacing visual user interfaces with Spatial Tactons. If the aim is to improve the performance of applying existing visual user interfaces, they can be augmented with Spatial Tactons.

### 7.3.3 What to display?

In general, this thesis has investigated presenting the direction and distance of one or several landmarks, waypoints, or friends. One of the findings across the reported experiments is that providing this reduced form of spatial information is not worse than providing detailed spatial information, such as maps or turn-by-turn instructions. Our participants showed that the human's inherent navigation skills often suffice if a general direction is provided. Detailed turn-by-turn instructions are not necessary and may even make the user feel patronised. Maps are appreciated for providing an overview but its use can be reduced by providing general directions only. Thus, Spatial Tactons should be used to convey general directions, such as the location of landmarks or people as points of reference. In addition, a map should be provided to allow users to get an overview.

## 7.4 Future Work

We have shown that it is possible to present the location of up to three spatial entities in sequential order, that we can encode eight directions in vibration patterns, and that we can encode seven distance classes in rhythm, duration, and intensity of vibration stimuli. However, this thesis has not investigated where the limits to these numbers are. How many spatial entities can be presented in serial order before the user cannot keep track of the individual entities anymore? There is also the question of context. In the experiment reported in Section 4.2, where we displayed two waypoints in serial order with the tactile belt, informal pilot tests had shown that in the lab users could also identify four different waypoints. However, once the tests were repeated outdoors the identification got considerably worse. The question is how different context factors, such as being outdoors or walking, interfere with the perception. Furthermore, it is not clear whether the system at hand requires as much level of detail as we can encode. For example, Tactile Compass users often suggested to reduce the number of directions to four instead of eight when employing it for waypoint navigation. Seven distance classes might also not be relevant for many tasks. Designers still lack reliable guidelines on what level of detail is sufficient.

The Tactile Compass, in particular, has shown to invoke cognitive load on the user, which presumably is caused by the need to interpret the vibration patterns and mentally map them to directions. Thus, we will need to investigate how to reduce the cognitive workload. One approach might be finding more suitable patterns. For example, if we decided to reduce the number of directions to encode to four, only, used four patterns using one, two, three, and four pulses could be easier to interpret.

One of the core assumptions of this thesis is that presenting directional information with respect to the body's egocentre is the most intuitive form of encoding directions. However, one could also imagine building a miniature version of a tactile belt, which could be worn as a wristband. The question here is, would the brain be able to use the

wrist as new egocentre without added cognitive workload? Would a stimulus on the inner side of the right arm be intuitively interpreted as left, because the stimulus occurs on the left side of the wrist? Or would it be intuitively interpreted as right, because it occurs on the right arm?





## List of Figures

1.1	Our senses are our primary means of obtaining spatial information sufficient for most tasks. However, when finding friends in a crowd, maintain one's orientation in a dense forest, or finding one's way through a foreign city they might not be able to provide the necessary information. . . . .	2
1.2	Since our senses are limited, we have invented a number of tools, such as maps (a), compasses (b), or satellite navigation systems (c), to extend our perception beyond them. . . . .	3
1.3	Recent advances in technology have enabled location-based services, such as interactive maps (a), navigation systems (b), or friend finders (c), that allow obtaining spatial information far beyond the capabilities of our senses. . . . .	4
1.4	Challenge <i>distraction</i> : the communication of the spatial information distracts the user from the environment. . . . .	5
1.5	Challenge <i>efficiency</i> : the spatial information is communicated in a way that is difficult to interpret. . . . .	6
1.6	Challenge <i>perception</i> : the spatial information is communicated by a sense that is temporarily or permanently impaired. . . . .	8
1.7	Illustration of the thesis structure . . . . .	13
2.1	Fundamental geometric concepts required to express spatial information from an egocentric perspective: direction and distance . . . . .	17
2.2	Amplitude: altering the magnitude of the stimulus oscillation. . . . .	20
2.3	Sensitivity Threshold Map (source: Weinstein1968) . . . . .	21
2.4	Frequency: the speed of the oscillation. . . . .	21
2.5	Duration: alternating the lengths of the stimulus. . . . .	22
2.6	Rhythm: composing complex patterns from several stimuli. . . . .	22
2.7	Two-Point Discrimination Threshold Map (source: Weinstein1968) . . . .	23
2.8	Waveform: shape of form of the oscillation. . . . .	24
2.9	Summary of Tacton parameters and their ability to encode information. . .	26
2.10	An illustration of the Sensory Saltation Effect [TP97]: the upper diagram illustrates the actual stimuli occurring at three different locations. The lower diagram shows the perceived locations of the stimuli. The open circles denote the perception of phantom locations that occur in-between two stimulus locations. . . . .	28
2.11	Results of the study on direction perception by [vE05a]: instead of the body midaxis as internal reference point, the results suggest the existence of an internal reference point for each body half. . . . .	30

2.12	Magic Wand metaphor (left): user learns about location of an object by pointing at it with a mobile device; Sixth Sense metaphor (right): location of an object is encoded in the vibration itself. . . . .	31
3.1	The drawback of simultaneous location encoding: objects can mask each other. . . . .	37
3.2	Novel approach we propose: convey the location of objects in a sequential order. . . . .	38
3.3	Duration-based distance encoding (DUR): the closer the object, the shorter it gets displayed. . . . .	40
3.4	Rhythm-based distance encoding (RHY): the number of pulses indicate the distance class ranging from one pulse for the inner class to seven pulses for the outermost class. . . . .	41
3.5	Intensity-based distance encoding (INT): the closer the object, the higher the intensity of the stimulus becomes. . . . .	42
3.6	The three levels of the independent variable of this experiment. . . . .	43
3.7	A participant trying to position the three figures to match the location perceived via the tactile belt. . . . .	44
3.8	The accuracy related dependent measures: the direction error ( $\alpha$ ), the distance error $ a - b $ , and the position error ( $p$ ). . . . .	45
3.9	The pointing direction is encoded in the relative length of two pulses. In this illustration the geographic reference point is somewhat to the right-hand side, so the first pulse remains short while the length of the second pulse is slightly increased. . . . .	53
3.10	The distance is encoded in the pause between a set of pulses. The shorter the pause becomes the closer the user is to the presented location. . . .	54
3.11	Confusion matrix. The numbers indicate the distance classes, where 0 = ahead, 1 = front-right, 2 = right, and so on. The dark red 25.7% has to be read that in 25.7% of all times where "front-right" was presented, it was mistaken for "ahead". . . . .	55
4.1	Using a handheld device for pedestrian navigation in an urban environment.	58
4.2	Route visualisation through a tactile look-ahead: in alternating order the current waypoint and the subsequent waypoint are displayed. The user can anticipate how the route will continue beyond the current waypoint.	60
4.3	The tactile belt we used for the Tactile Wayfinder. . . . .	61
4.4	The used Tactons: the heartbeat-like pulse (left) indicated the direction of the next waypoint. A single pulse (right) is used for the look-ahead waypoint. . . . .	62
4.5	A participant familiarises himself with the Tactile Wayfinder. . . . .	63

4.6	The results of the photo recall test showing the average number of errors per condition (no significant effect found). . . . .	66
4.7	One of the routes drawn by a participant after the evaluation. How accurate the participants could reproduce the routes were used to compare the spatial knowledge between the two conditions. . . . .	67
4.8	The results of the route drawing tests showing the accuracy of the drawings per condition (no significant effect found). . . . .	68
4.9	The NasaTLX scores per condition (no significant effect found). . . . .	68
4.10	The number of near-accidents per condition. The Tactile Wayfinder significantly reduced the number of near-accidents. . . . .	69
4.11	The average completion time per condition (no significant effect found). . . . .	69
4.12	The average number of navigation errors per condition. The Tactile Wayfinder significantly increased the number of navigation errors. . . . .	69
4.13	The average time being disoriented per condition (no significant effect found). . . . .	70
4.14	Two approaches of conveying spatial information by mobile phones proposed by Frohlich et al. . . . .	74
4.15	Screenshot of the PocketNavigator and the Tactile Compass used in this study. . . . .	75
4.16	The three evaluation routes covering the city centre of Oldenburg (the two test routes are not shown). Map by OpenStreetMap.org . . . . .	77
4.17	Screenshot of the PocketNavigator as used in the visual condition. . . . .	78
4.18	Navigation performance measures. . . . .	81
4.19	Cognitive workload measures. . . . .	82
4.20	Distraction-related measures. . . . .	83
4.21	Participant struggling to read the display due to sunlight reflections (left). Participant scanning for the next waypoint (right). . . . .	84
5.1	Cueing the direction of the travel destination with Spatial Tactons (here, using a Tactile Belt) to create an added sense of direction. . . . .	90
5.2	Sketch of the tactile belt (left), egocentric direction cueing with the tactile belt (right) . . . . .	91
5.3	Visualisation of the interpolating presentation technique [PHHB08]: two actuators at 0° and 60° are used to exemplarily display three directions (0°, 20°, and 40°). . . . .	92
5.4	The tactile belt used for the study. The flexible fabrics houses six vibrotactile actuators which equally distribute around the torso if the belt is worn. . . . .	93
5.5	Overview of the evaluation environment: Participants started at <b>A</b> . Then had to reach <b>B</b> and from there go to <b>C</b> (from <a href="http://www.openstreetmap.org/">http://www.openstreetmap.org/</a> ). . . . .	95

5.6	The paper map that was used in the study. The evaluation environment is located near the upper-left corner of the map. . . . .	96
5.7	Example of the paper map's inaccuracy: a pedestrian path is shown as a street on the map (air photo from <a href="http://maps.live.com">http://maps.live.com</a> ). . . . .	97
5.8	Route length per condition: in average, the tactile sense of direction caused the participants to take shorter routes. . . . .	99
5.9	Walking speed per condition: in average, the tactile sense of direction caused the participants to walk slower. . . . .	100
5.10	Completion time per condition: no significant effect on the time to reach the destination could be found. . . . .	100
5.11	The tactile sense of direction caused the participants to check the map less often. . . . .	101
5.12	The tactile sense of direction caused the participants to experience less disorientation events. . . . .	102
5.13	The map was found more helpful to decide how to turn at each junction than the tactile sense of direction. . . . .	102
5.14	Female participants rated the belt to be more helpful than male participants.	103
5.15	Female participants interacted more often visibly with the tactile belt. .	103
5.16	The city forest that we used as evaluation environment: the dots mark the three places we used as destination in the navigation tasks. . . . .	107
6.1	A crowded festival is a good example of a demanding environment, with a lot of sensory interferences, including darkness, artificial lights, chatting, and loud music. . . . .	118
6.2	The subjective ratings of the <i>demand of attentional resources</i> per condition. The tactile location presentation significantly lowered the demand of attentional resources. . . . .	124
6.3	The subjective ratings of the <i>supply of attentional resources</i> per condition. The tactile location presentation significantly improved the supply of attentional resources. . . . .	124
6.4	The subjective ratings of the <i>understanding of the situation</i> per condition. The tactile location presentation significantly improved the understanding of the situation. . . . .	125
6.5	The experimenters' ratings of the <i>accuracy</i> of the SPAM responses per condition. The tactile location presentation significantly increased how accurate the participants responded to the experimenters interruption. .	125
6.6	The experimenters' ratings of the <i>speed</i> of the SPAM responses per condition. The tactile location presentation significantly increased how fast the participants responded to the experimenters interruption. . . . .	126

6.7	The experimenters' ratings of the <i>certainty</i> of the SPAM responses per condition. The tactile location presentation significantly increased how certain the participants responded to the experimenters interruption. . . .	126
6.8	The participants' ratings of the team play per condition. The tactile location presentation significantly improved the participants' subjective rating of the team play. . . . .	127
6.9	The experimenters' ratings of the team play per condition. The tactile location presentation significantly improved the experimenters' subjective rating of the team play. . . . .	128
6.10	The Kramermarkt festival in Oldenburg, Germany, where the field study took place . . . . .	131
6.11	Screenshot of the visual component of FriendSense: direction and distance of all friends are shown in a radar-like UI. In the illustrated situation, two friends have strayed away from the group, which is to the left-hand side. The red dashed line indicates which friend the user has selected to be displayed via the tactile feedback. . . . .	133
6.12	The participants' ESM ratings of how relaxed they feel per condition. The tactile friend sense significantly increased how relaxed the participants felt. . . . .	135
6.13	The participants' ESM ratings of how the level of attention devote to the location of the others per condition. The tactile friend sense significantly subjectively decreased the necessary level of attention. . . . .	136
6.14	The participants' ESM ratings of how difficult the found keeping the group together per condition. The tactile friend sense significantly lowered the subjective difficulty. . . . .	136



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