Shoe me the Way: A Shoe-Based Tactile Interface for Eyes-Free Urban Navigation

Maximilian Schirmer[1], **Johannes Hartmann**[1], **Sven Bertel**[1], **Florian Echtler**[2]
[1]Usability Research Group, [2]Mobile Media Group
Bauhaus-Universität Weimar
Bauhausstr. 11, 99423 Weimar, Germany
firstname.lastname@uni-weimar.de

ABSTRACT
We present *Shoe me the Way*, a novel tactile interface for eyes-free pedestrian navigation in urban environments. Our prototypical implementation can be fully integrated into users' own, regular shoes without permanent modifications. Interface use does not distract users from their surroundings. It thereby adds to users' safety and enables them to explore their environments more freely than is possible with prevailing mobile map-based pedestrian navigation systems. We evaluated our prototype using two different navigation modes in a study with 21 participants and report on significant differences in user performance and preferences between the modes. Study results also show that even our prototypical implementation is already stable, functional and has high usability.

Author Keywords
navigation; tactile interface; eyes-free interface; wearable; mobile device

ACM Classification Keywords
H.5.m. Information Interfaces and Presentation (e.g. HCI): Miscellaneous

INTRODUCTION AND MOTIVATION
The proliferation and common use of mobile devices such as smartphones has greatly changed personal urban navigation over the last years and, with it, the relationships between users and space and place [20]. Before, people were mainly accustomed to using paper-based maps or to asking other people for directions. Nowadays, mobile map and navigation applications on mobile devices have become a primary class of wayfinding and navigation aids in urban environments. The reliance on automatic navigation systems seems to possess general consequences both for the kind and amounts of spatial knowledge that are acquired during navigation [15, 24].

MobileHCI'15, August 24–27, 2015, Copenhagen, Denmark.

ACM 978-1-4503-3652-9/15/08...$15.00.
DOI: http://dx.doi.org/10.1145/2785830.2785832

In contrast to regular, paper-based street-maps, mobile map-based applications offer a choice of spatial information on different levels of detail and situated, turn-by-turn instructions to keep users on the right way towards their intended target. Direct efforts associated with acquiring a mobile application (i.e., downloading it) will often be less than those associated with buying a paper-based map at a store. However, such advantages of mobile map-based applications come at the price of high attentional demands as users' visual attention has to be frequently directed at the display of the mobile device. As a consequence, people who stare at their smartphone, follow its instructions, and try to discern the right intersection to make a turn, have become a common sight in urban areas.

Figure 1: Overview of the *Shoe me the Way* components: Two vibration actuators are placed near the user's ankle, one on either side of the foot. The actuators are controlled by a microcontroller that is worn at the lower leg.

The growing amount of interaction with mobile devices during navigation tasks also greatly affects the interaction with the users' surroundings: because device interactions occur in frequent short bursts [13], sights or other interesting buildings and places along the way are often not recognised, and people more frequently bump into one another or into obstacles (e.g., into lamp posts or traffic signs) [11]. In 2010, the British motoring association AA projected that a significant amount of the 500 traffic deaths and 26,887 traffic casualties in the UK could be attributed to people focusing more on their mobile devices, and less on traffic and other road users [22]. In the same year, the phenomenon was dubbed "iPod Zombie Trance" or "Death by iPod" by the Internet community [12].

In this paper, we introduce *Shoe me the Way*, a new interface for personal urban navigation. The interface uses tactile feedback to convey situated turn-by-turn information. Tactile feedback is provided in the user's shoe, using vibration actuators. With *Shoe me the Way*, no visual attention on the mobile device is required once the user is on the way. Users are free to explore their surroundings during the wayfinding process. Two distinct navigation modes can be used, the *Navigator*, and the *Compass* mode. In a user study with 21 participants, we evaluated the performance, usability, and user experience of both modes, and of the interface in general.

The remainder of this paper is structured as follows: Next, we will discuss related work that is relevant to our approach. We will then introduce our concept and give a detailed overview of our interface prototype. Following this, we will report on our user study. The paper concludes with a discussion and an outlook on future research directions.

RELATED WORK

The research presented in this paper is primarily related to the field of navigation systems with tactile feedback. There exists a broad range of previous work, with either a single or with several actuators, that have inspired a number of aspects of and design decisions for our interface. Additionally, a few (e.g., commercial) products exist that include shoe-based interfaces.

Navigation with Several Tactile Actuators

Systems with multiple actuators generally seem to provide high accuracy in conveying directional information to users. Compared to systems with only one tactile actuator, they are heavier, though. Tactile feedback of the existing multi-actuator systems is usually rather easy to understand for users as actuators can be spatially arranged on the user to respectively correspond to different directional choices. For example, when an actuator vibrates that has been placed on the left side of the user's body, it is clear that the target direction is to be found to the left of the user.

Several research prototypes rely on using a belt with vibration actuators which are used to convey navigation information to users without the need for any visual feedback [7, 16, 19, 21]. While some of the existing prototypes were designed for use with vehicles, such as motorcycles [18] or bicycles [19], others were specifically aimed at use by pedestrians [4]. All of these prototypes have in common that actuators both convey the direction and distance of a navigation target. User studies have shown that users quickly understand such kind of feedback, that they achieved good direction accuracy (up to 15°), and that they were largely successful in completing navigation tasks. However, a belt with several vibration motors (up to 13 in some of the prototypes) can be a rather bulky device and most of the time too unwieldy and obtrusive to be included in users' everyday lives. This is especially true if the batteries are included in the belt. For *Shoe me the Way*, we explicitly aimed at a more portable, more light-weight, and more unobtrusive solution, that would still maintain a comparable level of understandability and accuracy to current belt-based approaches. As we will make clear below, such an approach does not preclude all non-shoe-based design options, such as systems incorporated into belts; however, a number of practical considerations informed the choice of shoe over other pieces of clothing.

Navigation with a Single Tactile Actuator

Devices with only a single tactile actuator can be small and can easily be integrated into various objects of clothing, pockets, or bags. However, using only a single tactile channel necessarily introduces an extra level of complexity to the user interface. While, with several actuators, mapping positions of vibration to directions around the user can be arranged to be quite obvious, a single actuator must encode directional information in a different way. Existing prototypes make use of an additional temporal encoding (i.e,. through direction-specific vibration patterns that have to be learnt and recalled by users).

The *PocketNavigator* [17] utilises the vibration motor of a regular Android smartphone to convey navigation information. A 2-pulse signal encodes directions for taking turns. The pulse length determines the direction: a short vibration followed by a long vibration means right; a long-short pattern means left. The signal duration provides a second level of resolution: when one of the pulses is twice as long as the other, the target is directly to the left or right. A signal with 4 times the duration of the other means to the left or right, half way behind the user. Conceptually, the duration of the longer signal encodes how long the user should turn in order to point directly to the target. The signal for "directly behind" does not follow this convention: 3 quick vibration pulses indicate that the user should turn around by 180 degrees. In a user study with *PocketNavigator*, the authors found that the tactile feedback increased the users' attention to the route. However, the continuous vibration feedback quickly drained the device's battery, and users found it annoying after some time.

HapticStayonPath, *HapticNavigator*, *HapticWayPointer*, and *HapticDestinationPointer* [8] are similar to the *PocketNavigator* in that they are also realised as smartphone apps and make use of the device's vibration system for tactile feedback. Within the prototypes, several encoding variants for navigation information have been implemented and tested.

Possibly the largest drawback of these approaches is the fact that they rely on the smartphone's compass: in order to function properly, the orientation of the device must be aligned with the user's orientation, which makes it impossible to carry the device in a bag, pocket or backpack. For *Shoe me the Way*, we explicitly aimed at a solution that would work reliably without such alignment constraints.

Other Shoe-Based Interfaces

Some art and commercial projects exist that provide feedback in or on a user's shoes during navigation tasks.

No Place Like Home [23] is an art project that features a pair of men's leather shoes which were specifically built for the project. The shoes are augmented with a micro controller, a GPS module, and a set of LEDs which are arranged in the toecap of the shoe. Users upload desired target coordinates to the shoe via a USB connection and are then guided by different light patterns as they walk around.

Lechal [2] offers a range of shoes and insoles that provide tactile feedback (through vibration motors), are equipped with motion sensors (accelerometer), and offer Bluetooth connectivity. As by the time of writing this contribution, it is still only an announced commercial product with unknown release date, only very little additional information about the technical details or modes of interaction is available right now.

Paradiso et al.[14] present work on a complex shoe-based sensor platform that can be used to gather various types of data about foot gestures and movements with high temporal resolution. This prototype was used for expressive, interactive dance performances, in which the dancer generated a stream of music based on shoe-embedded sensors.

CONCEPT

Shoe me the Way is a personal navigation assistance system interface with tactile feedback. We present a novel way of providing direction instructions for turn-by-turn-based navigation without any kind of visual or acoustic feedback, because these feedback channels have proven to be distracting, most notably in urban environments with many obstacles and other road users.

Design Rationale

After examining the more obvious placement options for a tactile feedback interface (e.g., in shirt or trouser pockets, near the user's hands, on a belt), we decided to design an interface that is placed in or near the user's shoe in the form of a wearable. This design decision was driven by the facts that, in urban environments, most users always wear shoes when they are outside their homes, that shoes provide suitable space to stow away hardware components, and that human feet provide sufficient sensitivity for receiving tactile feedback [6]. In comparison, while a belt would also provide enough space for all components, would potentially allow for a similarly lightweight design solution, and could be placed at a body position that offered sufficient tactile sensitivity, it would add another layer of clothing for people who do not regularly wear a belt. Secondly, belts are usually worn above other items of clothing, making it difficult to reliably set levels of vibration that are neither too strong nor too weak. Last, there might exist situations in which adding a belt may clash with a specific outfit (e.g., when wearing a dress), or would be considered inappropriate (e.g., when wearing formal attire). While we think our shoe-based solution is more universal, placing the components in or on a belt would likely result in a working system as well.

In view of our discussion of existing navigation systems with tactile feedback, we decided to use a small number of actuators, since the interface should be light-weight and easy to carry over longer periods of time. With *Shoe me the Way*, we wanted to create an immersive experience that lets users focus on the environment and their surroundings rather than on their navigational aid. Ideally, users will soon forget that they are being guided by a device. Therefore, unobtrusiveness and simplicity were our main design goals. Our wearable interface uses 2 actuators that are placed on opposing sides of one foot, just below the user's ankle (see Figure 1 for an illustration). With 2 actuators, we hope to get the best of two worlds: the comparably higher accuracy and better comprehensibility of a multi-actuator system, and the simplicity and low weight of a single-actuator system.

Actuator Patterns

Although an obvious approach would be to indicate turns to the left by vibrations in the left shoe and turns to the right by those in the right shoe, we decided against such a solution. Distributing the two actuators across both shoes would necessarily require a second communications channel and a second power source, thereby doubling the system's complexity. As shown in [6], the human foot is very sensitive to tactile stimuli (vibration), especially at the ankle in the medial region where we place *Shoe me the Way*'s actuators. We hypothesised at design time of the interface that users would be able to reliably differentiate between two different vibration sources in the same shoe if both would be placed sufficiently apart.

For encoding directional instructions (i.e., that a target is to the left, right, behind, or in front of a user), we devised 4 simple vibration patterns. These are illustrated in Figure 2. When the target is within a 90° area to the left or right, a low-frequency vibration with 0.5 Hz is triggered on the corresponding side of the shoe. When the target is within a 90° area directly behind the user, both actuators vibrate at a higher frequency of 2 Hz. When the target is within a 90° area just in front of the user, there is no vibration at all. The user does not need to be bothered with additional instructions when no change of direction is required at the moment. Figure 3 illustrates the target areas and their corresponding angles.

Interaction

Our prototype provides two distinct navigation modes that differ in terms of user interaction, frequency of given tactile feedback, and required hardware components. In both modes, the route from the current position to the next target of the navigation is dynamically computed and constantly updated. This permits the prototype to dynamically react to any voluntary or involuntary deviations that a user shows from a computed optimal route. As a consequence, wrong turns will usually not require that the user returns to the point of deviation from the precomputed route; instead, a new route will be computed.

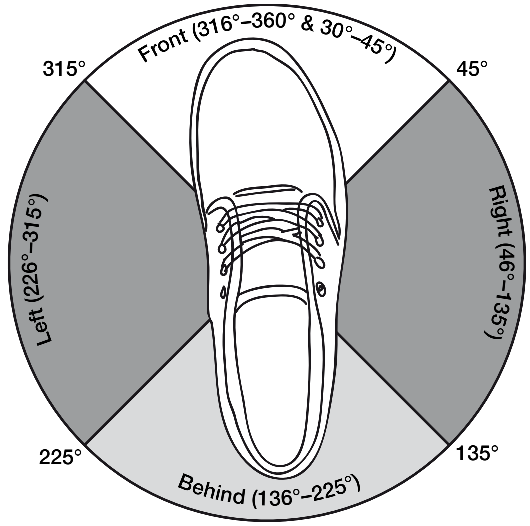


Figure 3: Overview of the target areas (left, right, behind, front) with their corresponding angular range. All angles are given relative to *in front of* the user (i.e., of his or her foot), not relative to north.

Navigator Mode

Operation of the *Navigator* mode is quite clear and straightforward. It works just like regular navigation systems that are, for instance, used in cars and only provides feedback when users are approaching intermediate targets (i.e., intersections): beginning at a distance of 50 m to the target, constant tactile feedback is provided to indicate the direction of the next turn. In a pilot study, we found that users were irritated when no feedback was provided on long straight sections in-between intermediate targets. As a consequence, we added a confirmation signal in the form of 2 short vibration pulses every 20 s, whenever an intermediate target was more than 50 m away. The only purpose of the confirmation signal was to tell the user that the interface was functional and that he or she could simply continue to walk in the current direction.

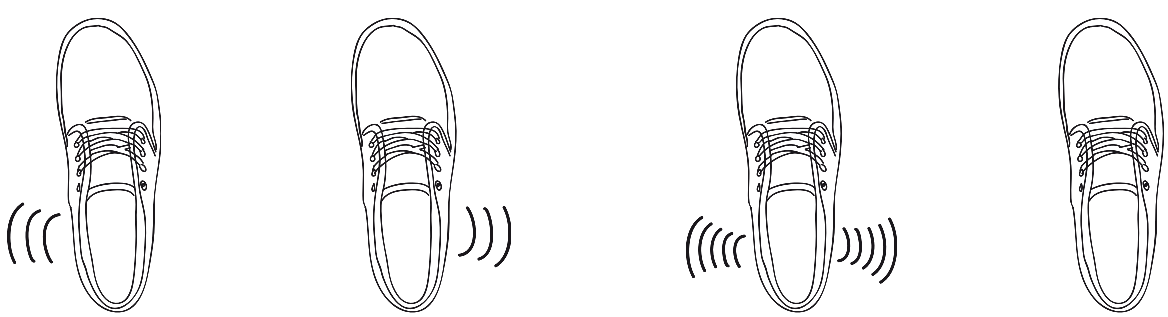
Compass Mode

The *Compass* mode makes use of a compass module that is part of our prototype, and provides continuous tactile feedback once the user stands still for a moment. In contrast to the *Navigator*, this approach is more exploratory and playful, and invites users to interact more with their navigation task. Basically, in this mode, tactile feeback is provided until users are pointing into the correct direction (i.e., the direction towards the next turn, or the routing target if there are no intermediate steps left). No feedback is provided while users are walking, because the compass accuracy is much decreased when the device is in motion. Thus, there is a chance that users might simply miss a turn because they did not stop in time to check for new instructions. This may happen when intersections are not clearly visible as such, or if other environmental conditions (pavement, crowded streets, road blocks, etc.) let users pass an intersection without checking. Since our interface constantly updates the navigation route, users will still always reach their target at the end with the *Compass* mode; the travelled route might just include detours and be a little longer than the route that had been originally calculated.

PROTOTYPE

In order to assess the feasibility, usability, and performance of our concept, we have built a prototype in the form of a distributed system. Hardware requirements were derived from the concept introduced above. The *Shoe me the Way* prototype consists of a microcontroller unit with a compass and a Bluetooth module, two vibration actuators, and a mobile application for Apple iOS. In the course of this paper, we will refer to the former as the *shoe component*, and to the latter as the *phone component*. The prototype can be installed in the users' own shoes, as long as they provide a little space between the foot and the inner padding of the shoes. Most sneakers, running shoes, or business shoes will work fine, while pumps, sandals, or high-shaft boots may possibly be problematic. An overview of the system's components and data flow is shown schematically in Figure 4.

For the *shoe component*, we have used an Arduino Pro Micro, since it has a very small size, but still provides enough pins and sufficient computing power for our prototype. We use Bluetooth Low Energy (LE), the most recent version of



(a) left (b) right (c) behind (d) front

Figure 2: Overview of vibration patterns for directional instructions. Turning left or right is indicated by a low-frequency vibration on the corresponding side of the shoe, behind is indicated by a high-frequency vibration of both actuators, and front is indicated by no vibration at all.

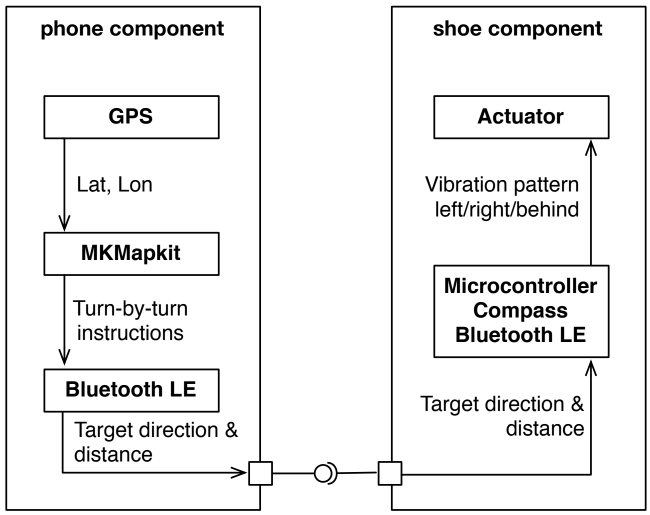


Figure 4: The *Shoe me the Way* component diagram.

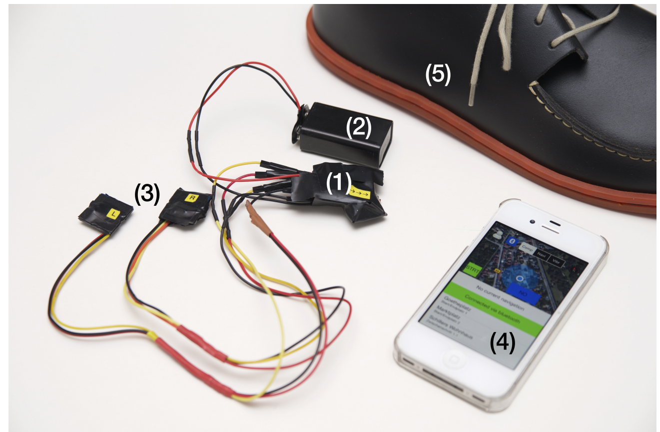


Figure 5: The *Shoe me the Way* hardware prototype, consisting of (1) a microcontroller with Bluetooth LE and compass modules, (2) a 9 V battery, (3) two vibration actuators, and (4) an iPhone 4s with our prototype application. Also in picture for size reference: (5) a size 8 (UK) men's shoe.

the Bluetooth protocol, which has a low energy footprint and allows our prototype to run off a standard 9 V battery for days. Bluetooth communication is currently one-way only: instructions are sent from the iPhone to the microcontroller, but not vice versa. The shoe component also includes a 9-DOF inertial measurement unit (IMU) with an accelerometer, magnetometer, and gyroscope. With these 3 sensors, we can compute the stabilised heading of the *shoe component*. The iPhone has a compass, however, a second compass needs to be located within the *shoe component* because the phone compass will often not be aligned with the user's viewing direction. We assumed that it is far more likely for the feet to be aligned with user orientation than it is for an iPhone. We want to allow users to put their phones in a pocket, bag, or backpack where and in whichever direction they prefer. The *shoe component* also holds two vibration motors, which are placed on each side of the user's foot to communicate the navigation instructions that we described in the *Concept* section. We aimed for a cost-efficient solution and consequently chose off-the-shelf vibration motors over other actuators (e.g., pneumatic actuators, heating elements, electrical stimulation) because they are easy to replace, low-cost, and work with a broad voltage range for different power sources.

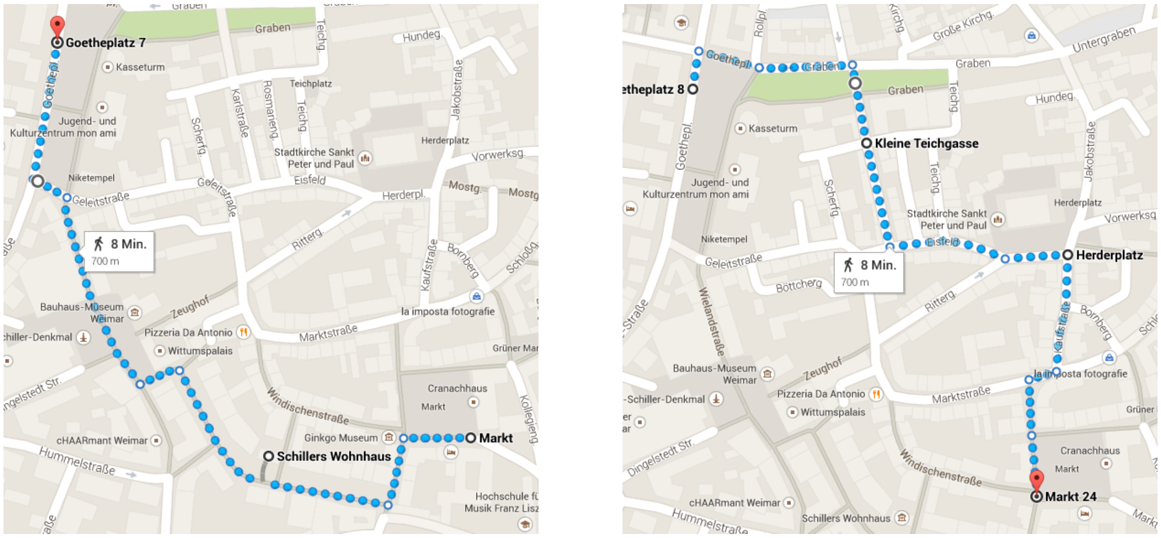
The *phone component* is an iOS application that utilises the smartphone's GPS facilities to provide situated, turn-by-turn routing information. The route is constantly updated to allow our prototype to dynamically adapt to wrong turns or to any deviations from a planned route. Based on a determined route, the application computes the navigation directions of the next turns. These can then be transferred to tactile feedback signals (left, right, behind, as introduced before) and be communicated to the user.

Once the appropriate signal has been determined, a corresponding command message is sent via Bluetooth to the microcontroller in the *shoe component*, along with other mode-dependant data. Such a signal is sent every two seconds. Depending on the current navigation mode, the actuators will then react accordingly. In the *Navigator* mode, command messages consist of a direction indicator and a distance-to-turn indicator. The microcontroller computes whether the target (i.e., the next turn) is close enough to start the tactile feedback. If the value is below the set threshold of 50 m, the actuators will then vibrate to indicate the transmitted direction. In case the prototype is set to *Compass* mode, the iPhone application first determines the angle between a vector from the user's position to magnetic North and a second vector from the user's position to the target (α). In order to determine the actual orientation of the user relative to the target, the compass angle of the user is also required. The iPhone's compass angle is not used instead as it will often not correspond to the user's orientation. The microcontroller consequently retrieves the current compass angle of the compass module in the *shoe component*, and offsets it with α. The resulting angle represents how the user's foot is orientated relative to the next turn and the appropriate tactile feedback is initiated.

The hardware of the prototype itself can be seen in Figure 5. It is compact, even though the system currently still is in an early hardware prototype stage. We were able to fit all the necessary components into a common sports workout pouch for smartphones, which can be comfortably strapped to the user's leg. The cables that connect the vibration motors to the microcontroller are placed on each side of the user's foot. There is no fixed position of where the motors have to sit inside the shoe in order for the prototype to work. Usually, some spot on the user's foot close to the ankle worked very well during our study.

EVALUATION

We conducted a user study in order to evaluate the usability and user experience of *Shoe me the Way* in general, and to find out particular differences between the 2 navigation modes. Our first set of hypotheses revolved around the recognisability of the tactile feedback. We hypothesised that there would



(a) Route 1 (b) Route 2

Figure 6: Map visualisations of the two route conditions in the user study. Both routes have the same length (700 m), the same number of intersections (10), and do neither include intersections with traffic lights. Route 1 leads from the market square (*Markt*) in Weimar to *Goetheplatz*, passing Friedrich Schiller's former residence (marked on the map as *Schillers Wohnhaus*). Route 2 leads from *Goetheplatz* back to the market square, via *Kleine Teichgasse* and *Herderplatz*. Map data ©2015 GeoBasis-DE/BKG (©2009), Google.

be no significant difference between recognising left and right vibrations, and that users would not make more errors recognising the behind pattern, compared to left and right. Another set of hypotheses focused on the actual use of the prototype and questioned whether users would perform better with one of the modes, and if our quantitative measurements (time to complete a route, errors made) would correspond to insights gained via the User Experience Questionnaire (UEQ) and the System Usability Scale (SUS). We hypothesised that there would be no significant difference in the time required to finish the route, and in the errors made between both navigation modes. We also hypothesised that the prototype would achieve higher SUS and UEQ scores for the *Navigator* mode than for the *Compass* mode, since we believe that the experience of using the former is more similar to that of using a regular car navigation system, to which most users are probably already accustomed.

21 participants took part in the study (13 male, 8 female). The mean of age was 23.43 years (SD = 2.66 years). 18 participants were students of computer science or of related subjects; 3 participants were students of political sciences. Participation was voluntary, and participants did neither receive remuneration nor credit points. The procedure of the study was explained to each participant, and all gave informed consent to data collection. 5 participants indicated that they had no prior knowledge of the urban area in which the study was conducted.

Part 1: Recognising Vibration Patterns

We began our study with an introduction to the different types of tactile feedback. Each participant experienced all 3 vibration patterns (left, right, behind) and was familiarised with their meaning. We then presented a series of 30 vibration samples in random order to the users and asked them to categorise each sample as either left, right, or behind. Each of the three vibration patterns was presented 10 times. The users stood still while the patterns were presented and indicated their answers both verbally and through hand gestures (i.e., lifting the right hand for a vibration on the right side of the foot, and left for left side).

The data very clearly shows that users found the three presented patterns easy to interpret and that they were able to recognise them very accurately. The achieved recognition rate was 99.7 %; users only misinterpreted 2 out of overall 680 samples. Based on this finding, it seems very safe to conclude that all 21 participants understood the respective meanings of the three vibration patterns. Although recognition accuracy may suffer slightly while walking [9], we can still assume that any mistakes which may have been made in subsequent parts of the study would be unlikely to be have been caused by erroneous interpretations of the vibration patterns.

Part 2: Experiencing Navigation Modes

In the second part of the study, users either started with the *Compass* or the *Navigator* mode, followed by the remaining mode. Similarly, they started with either Route 1 or Route 2, followed by the remaining route. As shown in Figure 6, we had two distinct routes between two major town areas in Weimar, Germany: from *Marktplatz* (market square) to *Goetheplatz*. Both routes are of the same length (700 m), contain the same number of intersections (10), and neither route contains intersections with traffic lights. Additionally, each route can be walked in either direction. We randomised the allocation of the route and navigation mode by means of Latin

	Navigator	Compass	Wilcoxon test statistics	Effect size
SUS Score	85.00 (*excellent*)	62.50 (*OK*)	$p < 0.001$, $z =$ -3.847	large, $r =$ -0.84
UEQ Attractiveness	2.00 (*excellent*)	0.50 (*bad*)	$p = 0.002$, $z =$ -3.061	large, $r =$ -0.67
UEQ Perspicuity	2.00 (*excellent*)	0.75 (*below avg.*)	$p = 0.001$, $z =$ -3.404	large, $r =$ -0.74
UEQ Efficiency	1.50 (*good*)	0.50 (*bad*)	$p < 0.001$, $z =$ -3.673	large, $r =$ -0.80
UEQ Dependability	1.50 (*good*)	0.00 (*bad*)	$p = 0.001$, $z =$ -3.405	large, $r =$ -0.74
UEQ Stimulation	2.00 (*excellent*)	1.25 (*above avg.*)	$p = 0.004$, $z =$ -2.862	large, $r =$ -0.62
UEQ Novelty	1.75 (*excellent*)	1.50 (*good*)	$p = 0.049$, $z =$ -1.969	medium, $r =$ -0.43

Table 1: Detailed results of medians for SUS scores and individual UEQ sub-scores. Wilcoxon test was consistently chosen for pairwise comparisons between *Navigator* and *Compass* modes, as previous tests with Shapiro-Wilk had shown non-normality for a number of variables. The Wilcoxon tests revealed that, for nearly all lines in the table, differences are highly significant; for the UEQ novelty dimension, the difference is significant. Effect sizes are nearly all *large*; again, an exception is the UEQ novelty dimension, for which the effect size is *medium*. Effect size categories for Pearson's r have been assigned after [1].

square to ensure that, across our sample, each combination was present equally often. We explained the first navigation mode to the users and asked them to simply follow the directional instructions that they received. We made it clear that there would be no incorrect route and that participants would just have to reach some unknown target, as indicated by the directions from the interface. Our goal was to create a setting similar to a casual stroll through town. All participants were equipped with a microphone and recording device, and were asked to verbally report on inconsistencies, uncertainties, expectations, or any errors which they might encounter on their route. All participants were followed by an observer who took notes on any errors or irregular events. Participants' GPS position was logged every 10 s. Every participant completed both routes, for a total track length of 1.4 km.

Once participants had arrived at their first route's final position, they were asked to complete UEQ and SUS questionnaires for the navigation mode that they had used on this route. The study then went on with the remaining route and mode, again with UEQ and SUS questionnaires at that route's final position. Participants were then also asked which of the two modes they preferred.

Just as to the first part of the study, the second part also produced clear results: Route completion was significantly faster with the *Navigator* mode (*Mean* = 9.72 min) than with the *Compass* mode (*Mean* = 15.2 min; $t(20) = 6.374$, $p < 0.001$, $r = 0.887$, t-test; data was normally distributed as tested with Shapiro-Wilk). According to the Google Maps service, estimated completion times of either route was 8 min. In the *Compass* mode, participants made significantly more errors while navigating than in the *Navigator* mode (*Mean* = 1.52 and *Mean* = 0.14, respectively; z = -3.337, p = 0.001, r = 0.781, Wilcoxon test; data was not normally distributed as tested with Shapiro-Wilk). We categorised two types of events as errors: taking a wrong turn (i.e., users went astray, did not follow an indicated direction at an intersection, or walked past an intersection where they should have taken a turn), and disorientation (i.e., users took a long time to figure out which way to go, or walked around erratically).

Data gathered from the questionnaires administered at the end of the routes also provides a clear picture: 19 participants stated that they preferred using the *Navigator* mode; only 2 participants stated that they preferred using the *Compass* mode.

As shown in Figure 7, for the *Compass* mode, the .95 confidence interval for the SUS score lies between 54.0 to 60.8 (*Median* = 62.5), resulting in a borderline between a classification as "OK" or "good". Values were significantly better for the *Navigator* mode: 81.2 to 88.3 ("good" to "excellent"; .95 confidence interval, *Median* = 85.0). A Wilcoxon test showed a highly significant difference between the results of the *Compass* and *Navigator* modes ($p < 0.001$, $z =$ -3.847) with a large effect size ($r =$ -0.84), see also Table 1 for further details.

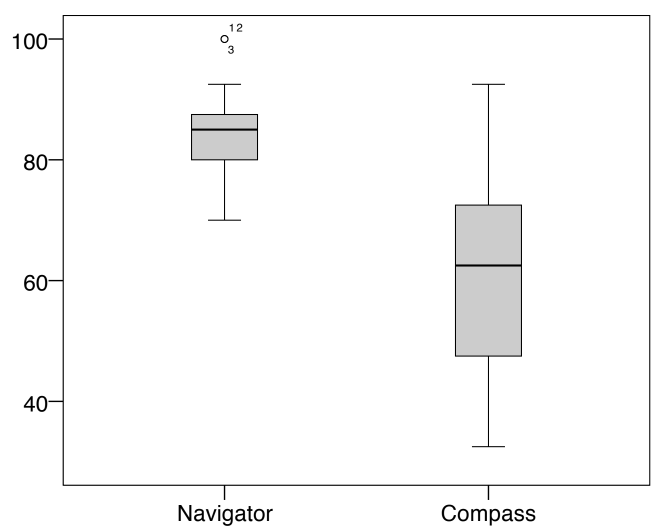


Figure 7: Boxplot of SUS scores for the *Navigator* and *Compass* modes.

Results for the UEQ questionnaire showed that the *Navigator* mode produced significantly better results than the *Compass* mode in all 6 categories (attractiveness, perspicuity, efficiency, dependability, stimulation, and novelty; cf. Figure 8

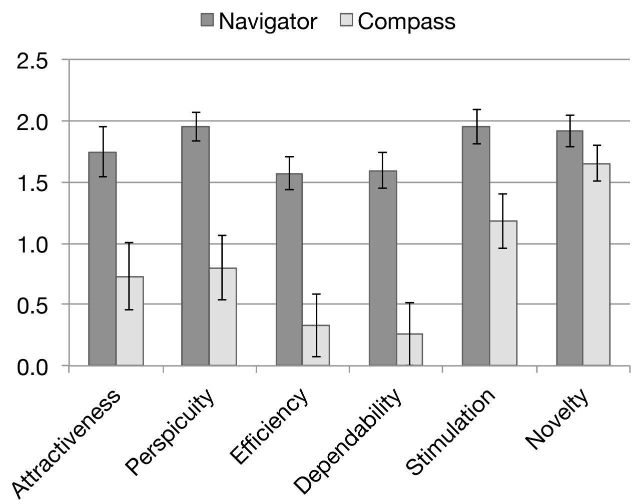


Figure 8: UEQ scores for the *Navigator* and *Compass* modes. Error bars represent standard error.

and Table 1). Furthermore, the only category in which the *Compass* mode was rated as "good" was novelty. We believe that this category does not necessarily rate the navigation mode itself, but may potentially rather reflect the general idea of having tactile feedback in a user's shoe during a navigation task. If so, then the result for novelty can be interpreted as a positive review of the original and creative character of our concept and prototype.

Results from our qualitative data (we recorded opinions and statement of the participants during the walks with a voice recorder) were equally clear: all users enjoyed using the device. While, before the study, many users stated that they were doubtful whether they would enjoy the experience, after the study, all users reported that they were positively surprised about how intuitive the device eventually was and that it did not feel like a foreign object to them. We had aimed at making the study context to feel as little as possible like an artificial, experimental setup, and our data suggests that we achieved this goal. We were able to engage in casual conversations with the users, aimed at distracting them from the fact that a study was taking place. This is the context of having a casual walk in the city while being guided by one's shoe. One user even stated, after having concluded the study and when filling in the final questionnaires, that she found "*the test to be so unlike a usual usability study, that I almost forgot why we were here*" (own translation from German).

In summary and based on the data gathered via the user study, our 4 major findings are: (1) The idea of using tactile feedback with vibration motors is advisable in a navigation task, and it is possible to encode four coarse directional instructions with 2 vibration motors such that people are able to interpret the instructions without any problems. This is not only supported by the quantitative data which we gathered, but also by the qualitative data. Various users stated that they "*enjoyed how straightforward the device eventually was*" (own translation from German). (2) Even with both actuators mounted in a single shoe, users can still reliably differentiate directional cues. (3) The *Navigator* mode seems to fit the purpose very well; compared to the *Compass* mode, users completed the navigation tasks faster and with fewer errors. (4) All test users reached their intended targets without any kind of intervention by the observer, and within reasonable times. For the largely preferred *Navigator* mode, these times were also close to the time estimated by the routing service.

DISCUSSION

Our *Shoe me the Way* prototype implements a novel interface for eyes-free urban navigation. As our evaluation shows, it is stable, functional, and has high usability. In comparison to similar approaches, our interface stands out because of its placement on the user's foot. A major advantage is that *Shoe me the Way* does not require users to hold or carry their smartphones in specific ways in order to be able to navigate properly. We were able to show that the interface is well suited to fulfil its function. The results of our quantitative measurements (SUS, UEQ) are very clear. These have shown that our interface performs remarkably well in regard to general usability and user experience, and was quickly accepted by all users in our user study. The benchmark results in the UEQ for the *Navigator* mode were *excellent* except for 2 categories which were still rated as *good*, an extraordinary result for the early design state of our prototype.

The *Compass* mode did not achieve similarly high UEQ and SUS ratings. This may well be due, in part, to the fact that the compass within the *shoe component* required users to stand still for a moment before new status information could be given (please also see the future work section below on this point). Secondly, we believe that an approach that purely relies on directional information and that omits information about waypoints (such as our *Compass* mode) may be less suited for use in a highly structured urban environment than approaches that do encode waypoint information (e.g., our *Navigator* mode). It may be worthwhile to repeat our study in less structured environments that are more amenable to dead reckoning strategies, for instance in an open park. Additionally, and as we had hypothesised above, the *Navigator* mode may have had an initial advantage over the *Compass* mode due to a familiarity of users with car navigation systems: instructions provided by such systems commonly are based on making turns at next decision points and are comparable in function and structure to instructions generated in the *Navigator* mode.

Our results not only indicate that a shoe-based tactile interface is possible, but also that users enjoy using it. This is a major factor and can be transferred to others uses and application scenarios. While we assume that, due to a natural mapping of left/right vibrations to directions in space, navigation performance can especially profit from such an interface, other types of information may easily be signaled to a user. A potential scenario would be to let the shoe vibrate as users approach shops in a shopping centre that offer special sales. Different vibration patterns may then indicate different sale opportunities. [5] described a related shoe-based interface for watching the stock market.

Participants in our evaluation study stood still in the first part; they walked and stood in the second part. We believe that the very high recognition rates of the employed three vibration patterns in the first part also point to very high recognition rates during the second part. However, other research reported a decrease of vibro-tactile perception on the foot while walking [9]. It thus seems sensible to check what effect the combination of a slow gait with intervals of standing still has on the recognition rates of our three patterns.

As discussed earlier [20, 15, 24], using interactive navigation aids will likely affect the spatial knowledge that is created about a spatial environment, compared to using paper-based maps or to using no maps at all. It seems plausible that the use of a tactile navigation interface such as *Shoe me the Way* will have similar effects. However, it seems similarly plausible that such effects may be less pronounced than with mobile map-based interfaces: as various studies show [17, 3], using haptic feedback can increase awareness and attention to environmental features. It is likely that such findings can be translated to *Shoe me the Way*. It seems reasonable to assume that users can direct more of their (visual) attention to their environment when less (visual) attention is required for interaction with a navigational aid.

FUTURE WORK

We intend to further investigate the relationships between users of *Shoe me the Way* and space and place around them. We are especially interested in the kinds and types of mental representations that users construct from navigating an urban environment with our interface, and are currently setting up a follow-up study. This study will aim at comparing how much attentional resources users can direct to environmental features when using *Shoe me the Way* compared to when using mobile map-based navigation aids.

It seems worthwhile to also integrate the distance indicator of the *Navigator* mode into the *Compass* mode. Even with the currently used hardware in the *shoe component*, this would mean that users would no longer have to stand still for a few seconds at every intersection in order to check for a possible turn: users would simply walk and be notified in time whenever they approach a turn. Such combination of the modes may, however, take away some of the perceived ease and liberty of navigating with the *Compass* mode, as users would lose some control over when navigation instructions are provided by the interface. The concept of implementing a combined mode was also frequently expressed by participants in the study: as a participant noted, he or she could "*imagine that the system could very well use both modes in combination, or make it possible to switch between the modes*" (own translation from German).

As *Shoe me the Way* only uses two actuators, one to the left and one to the right of the user's foot, indicating turns at intersections at which more than four routes meet poses some challenges. In our user study, performance at such intersections was not explicitly tested. One design solution may be to combine the two modes such that the *Compass* mode gets triggered during the *Navigator* mode whenever the user reaches a complex intersection. The user could then gradually turn at the intersection, and chose the route option indicated by the *Compass* mode.

It might be interesting to experiment with expanding the hardware components that are currently being used for the prototype. Especially for the *Compass* mode, dividing the directional space around the user into four equal parts (front, left, right, behind) may not always provide sufficient angular resolution. If one doubled the number of actuators, the interface may indicate turns such as "to the front/left" in more intuitive ways than is possible with just two actuators. Adding yet more actuators would likely bring up new challenges of discretisation for the interface: Our study has shown that users are perfectly able to distinguish the tactile feedback of 2 vibration motors at 2 opposite positions on their foot. Would they be equally able to distinguish the tactile feedback from 4 or 8 actuators? Similarly, the current 2-actuator setup may be used to provide more vibration patterns than are currently employed: These may, for example, be used to indicate finer distinctions in turn-taking, such as between slightly veering to the left, taking a 90-degrees turn, or going sharp left. Research on giving route directions has shown that, conceptually, models with up to eight sectors can usually be well understood by users in pedestrian navigation, though sectors should not necessarily be of uniform angular size (i.e., 45 degrees) [10].

Last, it may be profitable to experiment with providing directional instructions not simply through different actuators but also through variations of the length and strength of the tactile feedback. A longer signal could mean that a target is more in the prototypical centre of a directional sector (e.g., "directly to the left"), whereas a shorter signal could mean "slightly to the left". In any case, it is also imaginable to replace signal length by signal strength. Again, a question of limits of sensory discretisation would arise. Suitable step sizes and numbers of discrete steps will need to be evaluated in further user studies.

ACKNOWLEDGEMENTS

We would like to thank Stefanie Wetzel for the valuable support in the evaluation, Anna-Katharina Rack for her help with the illustrations of this paper, all 21 participants for taking part in our study, and five anonymous reviewers for their valuable comments and suggestions.

REFERENCES

1. Cohen, J. *Statistical power analysis for the behavioral sciences*. Academic press, New York, 1988.
2. Ducere Industries. Lechal soles - interactive haptic footwear. http://www.lechal.com/, 2014. Accessed: 2015-02-05.
3. Duistermaat, M., Elliot, L. R., van Erp, J. B. F., Redden, E. S., de Waard, D., Hockey, B., Nickel, P., and Brookhuis, K. *Tactile land navigation for dismounted soldiers*. Maastricht, The Netherlands, 2007, 43–53.
4. Frey, M. Cabboots: Shoes with integrated guidance system. In *Proceedings of the 1st International*

Conference on Tangible and Embedded Interaction, TEI '07, ACM (New York, NY, USA, 2007), 245–246.

5. Fu, X., and Li, D. Haptic shoes: representing information by vibration. In *APVis '05 proceedings of the 2005 Asia-Pacific symposium on Information visualisation - Volume 45* (Darlinghurts, Australia, 2005), 47–50.
6. Hennig, E. M., and Sterzing, T. Sensitivity mapping of the human foot: Thresholds at 30 skin locations. *Foot & Ankle International 30*, 10 (2009), 986–991.
7. Heuten, W., Henze, N., Boll, S., and Pielot, M. Tactile wayfinder: a non-visual support system for wayfinding. In *NordiCHI '08 Proceedings of the 5th Nordic conference on Human-computer interaction: building bridges* (Lund, Schweden, 2008), 172–181.
8. Jacob, R., Mooney, P., and Winstanley, A. C. Guided by touch: tactile pedestrian navigation. In *MLBS '11 Proceedings of the 1st international workshop on Mobile location-based service* (Beijing, China, 2011), 11–20.
9. Karuei, I., MacLean, K. E., Foley-Fisher, Z., MacKenzie, R., Koch, S., and El-Zohairy, M. Detecting vibrations across the body in mobile contexts. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '11, ACM (New York, NY, USA, 2011), 3267–3276.
10. Klippel, A., Dewey, C., Knauff, M., Richter, K.-F., Montello, D. R., Freksa, C., and Loeliger, E.-A. Direction concepts in wayfinding assistance systems. In *Workshop on Artificial Intelligence in Mobile Systems (AIMS'04)*, SFB 378, Memo 84 (Saarbrücken, 2004), 1–8.
11. Madden, M., and Rainie, L. Adults and cell phone distractions. Tech. rep., Pew Research Center, 2010.
12. Murphy, D. Pedestrian death rise blamed on iPods. http://www.theage.com.au/digital-life/mp3s/pedestrian-death-rise-blamed-on-ipods-20100905-14w4d.html, 2010. Accessed: 2014-05-02.
13. Oulasvirta, A., Tamminen, S., Roto, V., and Kourelahti, J. Interaction in 4-Second Bursts: The Fragmented Nature of Attentional Resources in Mobile HCI. In *CHI '05 Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (Portland, Oregon, USA, 2005).
14. Paradiso, J., yuh Hsiao, K., Benbasat, A., and Teegarden, Z. Design and implementation of expressive footwear. *IBM Systems Journal 39* (2000), 511–529.
15. Parush, A., Ahuvia, S., and Erev, I. Degradation in spatial knowledge acquisition when using automatic navigation systems. In *Spatial information theory*. Springer, 2007, 238–254.
16. Pielot, M., Henze, N., and Boll, S. Supporting map-based wayfinding with tactile cues. In *MobileHCI '09 Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (Salzburg, Österreich, 2009).
17. Pielot, M., Poppinga, B., and Boll, S. PocketNavigator: vibro-tactile waypoint navigation for everyday mobile devices. In *MobileHCI '10 Proceedings of the 12th international conference on Human computer interaction with mobile devices and services* (Lisbon, Portugal, 2010), 423–426.
18. Prasad, M., Taele, P., Goldberg, D., and Hammond, T. A. Haptimoto: Turn-by-turn haptic route guidance interface for motorcyclists. In *Proceedings of the 32Nd Annual ACM Conference on Human Factors in Computing Systems*, CHI '14, ACM (New York, NY, USA, 2014), 3597–3606.
19. Seltenpohl, H., and Bouwer, A. Vibrobelt: tactile navigation support for cyclists. In *IUI '13 Proceedings of the 2013 international conference on Intelligent user interfaces* (Santa Monica, CA, USA, 2013).
20. Speake, J. 'I've got my sat nav, it's alright': Users' attitudes towards, and engagements with, technologies of navigation. *The Cartographic Journal*. In press.
21. Velãzquez, R., Bazán, O., and Magaña, M. A shoe-integrated tactile display for directional navigation. In *Proceedings of the 2009 IEEE/RSJ International Conference on Intelligent Robots and Systems*, IROS'09, IEEE Press (Piscataway, NJ, USA, 2009), 1235–1240.
22. Wattanajantra, A. Zombie 'iPod pedestrians' endangered by mobile oblivion, says AA. http://www.cnet.com/news/zombie-ipod-pedestrians-endangered-by-mobile-oblivion-says-aa/, 09.08.2010. Accessed: 2015-02-05.
23. Wilcox, D. No Place Like Home, GPS shoes. http://dominicwilcox.com/portfolio/gpsshoe/, 01.01.2012. Accessed: 2015-02-05.
24. Willis, K. S., Hölscher, C., Wilbertz, G., and Li, C. A Comparison of spatial knowledge acquisition with maps and mobile maps. *Computers, Environment and Urban Systems 33*, 2 (2009), 100 – 110.