Exploring Vibrotactile Feedback on the Body and Foot for the Purpose of Pedestrian Navigation

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ABSTRACT
In this paper, we present an evaluation of vibrotactile onbody feedback for the purpose of pedestrian navigation. For this specific task, many researchers already provide different approaches such as vibrating belts, wristbands or shoes. Still, there are issues left that have to be considered, such as which body position is most suitable, what kind of vibration patterns are easy to interpret, and how applicable are vibrotactile feedback systems in real scenarios. To find answers, we reconstructed prototypes commonly found in literature and continued to further evaluate different foot-related designs. On the one hand, we learned that vibrotactile feedback at the foot reduces visual attention and thus also potentially reduces stress. However, on the other hand, we found that urban space can be very diverse, and ambiguous and therefore a vibrotactile system cannot completely replace common path finding systems for pedestrians. Rather, we envision such a system to be applied complementary as an assistive technology.

Author Keywords
Tactile Feedback, Vibration, Vibrotactile, Pedestrian Navigation, Assistive Technology, Intelligent User Interfaces.

ACM Classification Keywords
H.5.m. Information interfaces and presentation (e.g., HCI): Miscellaneous.

INTRODUCTION
Many studies show that navigation in unknown environments is traditionally accomplished with visual aids [25]. The majority of people use a smartphone for such a task nowadays. Even though directional feedback (such as *"turn left, right, …"*) is almost binary, using a smartphone many senses are still strained. By using devices such as a smartphone, the visual attention is heavily drawn, which makes navigating potentially dangerous while being involved in traffic, as has been shown in several studies [10,23,45]. A recent survey [10] reported that 62% of smartphone users below the age of 30 stated to have been at least once involved in a critical traffic situation caused by focusing on their smartphones instead of their surroundings – 43% even stated to be conscious of this potential danger. Especially when being involved in traffic, keeping the visual attention on the road is crucial. Alternative assistance systems can help in this case to decrease a cognitive load, such as demonstrated for the task of driving [20,21,45] or pedestrian navigation [28,35,45]. Like the driver, the pedestrian also perceives his/her environment mostly visually, but also acoustically. However, alternative assistance for pedestrians like acoustic information might not be the best solution, since the level of surrounding noises can be quite high close to roads. Therefore, we agree with Hornecker et al. [14], that this is not an appropriate solution.

The social aspect should also be considered as wearing headphones might be regarded as inadequate [28]. Instead, relying on vibrotactile onbody feedback possibly enables eyes- and hands-free interaction, since a smartphone is not needed to be held by the users. Supplying the user with directional aids via tactile onbody feedback will not distract the user from perceiving their surroundings. Another practical advantage of vibration is, that it is perceivable through clothes and can be easily embedded into everyday wearables, such as a belt [8] or an insole [24].

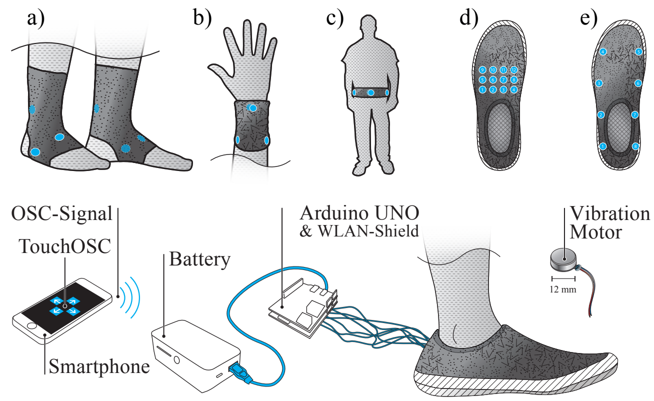

Figure 1. In this paper we explored vibrotactile onbody feedback for the purpose of pedestrian navigation. We evaluated different setups: a) sock bandages b) wristband c) belt d) insole matrix layout and d) side wall of the shoe.

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To evaluate the capabilities of vibrotactile onbody feedback for the purpose of pedestrian navigation, we had to test different body positions and the perception for different designs. Therefore, we built several prototypes, conducted five studies and contributed the following insights:

- Our studies reveal the foot to be capable in perceiving vibrotactile signals quite precisely. In our study, the foot interface performed slightly better than the wristband and the belt. This result is also supported by the fact that the foot has more sensory cells than the human face [22] and yields a higher resolution for haptic perception [9] than other parts, which are commonly used for vibrotactile feedback. In our studies, we could achieve acceptable accuracy rates while walking: Ø ~86.5% (wristband), Ø ~87% (shoe), Ø ~94% (belt), Ø ~100% (sock bandage)
- With increasing walking speed, the perception of vibrotactile onbody feedback is negatively affected. The accuracy rate at the foot significantly dropped by Ø ~15% from standing to jogging.
- Our studies and the in-situ field study in particular indicate that vibrotactile onbody feedback does not seem to be capable to be used as a stand-alone technology for pedestrian navigation, since it cannot provide precise enough information for the very diverse environment found in the city. Instead, we believe such feedback systems to be complementary as an assistive technology.

RELATED WORK

In literature, we can find four application scenarios for abstract information delivery of vibrotactile feedback, which are Communication, Navigation, Mobile Devices and Vehicles as set out by Choi et al. [6]. In this paper, we focus on the navigation scenario for pedestrians in urban space.

Nowadays, the task of navigation still mainly relies on the sensor channel of our visual perception, which is however also demanded to focus on traffic and other surroundings. Therefore, we and other researchers [14,44] believe that considering other channels would reduce the visual load. Additionally enabling the user to interact free-handedly makes interaction safer as we enable the user to accomplish real-world tasks, such as carrying bags, pushing a pram etc.

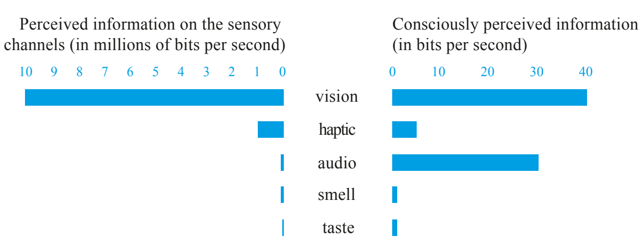

Figure 2. Actual neuro-chemical perceived information of sensor channels compared to consciously perceived information – based on Nørretranders [26].

Besides visual perception, humans are also capable of perceiving information through many different channels (*see figure 2*). Following visual perception, the sense with the second highest bandwidth is audio. However, in public spaces audio is often not an appropriate channel for the purpose of navigation, since surroundings often create huge amounts of noise and headphones could isolate the user and might cause dangerous situations (e.g. because/when the user is not able to hear a nearing motorcycle). Therefore, research focuses on utilizing the haptic sensation as an alternative feedback modality.

Sensory cells on our skin interpret mechanical forces such as pressure, touch, vibration and strain into nerve impulses, called mechanoreceptors [7,47]. Also, the ability to perceive temperature changes belongs to the category of haptic sensation.

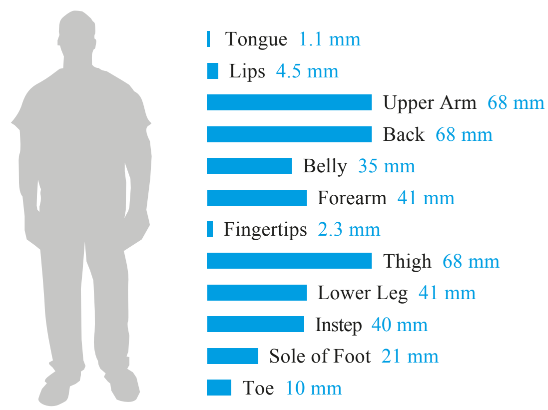

Figure 3. Resolution of haptic perception on the surface of the human body – based on Deetjen et al. [9]

Although haptic feedback can be transposed in many ways, most researchers commonly make use of vibration feedback. In figure 3, we can see the resolutions of different body parts, in which one point of sensation needs to be apart from another to perceive a difference. As can be seen, the tongue and fingertips provide a very high resolution, but have not been utilized for providing feedback since these positions are quite impractical for the user. Instead, the belly, forearm, hand, thigh, and the sole of the foot have all been frequently used for providing vibrotactile feedback for the purpose of navigation. Besides the resolution, haptic perception is also affected by the use of signal length, intensity and rhythm [4].

Vibrotactile Feedback for Navigation

Even though verbal cues can provide more accurate commands than vibrotactile feedback for spatial guidance [43], impaired users like deaf or blind people [2] cannot profit from commonly navigation aids. These user groups have an urgent need for assistance when moving in unknown public spaces. Assistive technologies could be wearable devices such as belts, wristbands, shoes or even smartphone applications, which are available at the user's body anyway.

Handheld Device. In "I did it my way" from Robinson et al. [32] or "NaviRadar" from Rümelin et al. [35], the user is required to hold a smartphone or a similar device in their hand to perceive vibration, which conveys the idea of the angle in which the user possibly needs to turn. In “Traxion” [33], Rekimoto proposes a handheld actuator (made of an electro-magnetic coil, a metal weight and a spring) to use a virtual force as a virtual pathfinder. In “Tacticycle” [30,37], they rely on the fact that certain tasks such as riding a bicycle, in which the user already needs to touch objects or devices, such as the handle bar of a bike. Therefore vibration motors are attached to both sides of the handle bar, thus enabling navigation assistance. However, we consider hand-held devices as guidance for pedestrians to be highly impractical, since they possibly need to be held in a certain position and therefore hinder the user from accomplishing real world tasks.

Smartphone in the pocket. While the smartphone is resting in the pocket, it is not obtrusive to the user, but enables the user to understand different vibration patterns on their thigh through worn clothes. Drawbacks are that angle data cannot be transmitted efficiently and users have to learn the specific vibration patterns, which are assigned to actions. This concept has been implemented in “PocketNavigator” [29] and “Navibration” [1].

Wristband. Another example of using onbody vibrotactile feedback for navigation, which is hands-free, is using an arm-/wristband as proposed by Kammoun et al. [17], Brock et al. [5] or Panëels et al. [27]. In the wake of the emergence of smartwatches, this position appears to be an area that seems interesting for further investigation. However, it is still an extra accessory which one would have to wear.

Belt. Compared to related concepts, vibrotactile belts have been very widely explored. In 2004 Tsukada et al. [38] proposed “ActiveBelt”, a belt and haptic feedback system with 8 vibration motors attached in a 45° angle, to accomplish a GPS navigation via vibrotactile feedback. Basically, the same setup was presented by Van Erp et al. [39], which showed promising results for the evaluation of two navigation scenarios on a boat and in a helicopter. A pedestrian navigation of a vibrotactile belt was evaluated by Heuten et al. [13] and Zöllner et al. [46]. Recently, Cosgun [8] additionally utilized a human motion tracking system to provide accurate path navigation with a vibrotactile belt. Tactile navigation for cyclists has also been explored recently by Steltenpohl et al. [36].

Shoe. As a matter of fact, feet are very sensitive, since they have significantly more sensory cells than the face [22]. Therefore, the foot is predestined as another position for feedback. Velázquez et al. [41,42] integrated 16 vibration motors in a design of a matrix into a shoe insole to provide vibrotactile feedback underneath the foot for the purpose of navigation. Instead of using vibration motors, Frey built “CabBoots” [11], which contain electro motors in a very thick insole that changes the weight distribution within the shoe sole. In this way, path navigation can also be enabled as demonstrated. These works propose the vibrotactile perception on the foot as a feedback channel, however, extensive evaluations between side/sole/other body positions for realistic use cases have not been presented yet.

Jewelry. In 2001, IDEO introduced the concept of a wearable technology in the form of jewelry. In “Technojewelry” [15], a vibrating ring is being proposed to be worn at the user’s finger or toes, which is able to give directions through vibrations via a GPS connection. **“**Pull-Navi” [19] describes future earrings, which are able to give directions through haptic force as well. In contrast to the previous project, “Pull-Navi” also presented a working prototype, which was rather cumbersome, but informally tested with about 100 participants. Nevertheless, this technology is still obtrusive due to size factors.

STUDY SETUP

Overview

There have been many investigations made on vibrotactile feedback for the purpose of navigation. However, most concepts have only been tested in lab environments and there is no evidence whether vibrotactile feedback is beneficial or even applicable to actual pedestrian navigation tasks where many external influences are present.

Firstly, it had to be determined which body positions of the proposed concepts would work best and are feasible to be implemented in a real product. In a second step in our study, we evaluated two designs for foot interfaces proposed in literature and whether wave-like patterns or simple vibration patterns are preferred as feedback. Thirdly, we investigated the influence of different walking speeds and the effect of an additional precursor signal. Subsequently, we conducted a stress test to find out the difference between visual and vibrotactile feedback in a stressful situation while navigating. Finally, we conducted an in-situ field study in which we wanted to evaluate the applicability and capabilities of such vibrotactile systems for the purpose of pedestrian navigation in urban space. The following five studies will give answers to our five hypotheses, which have been successively developed.

Hypotheses

H1: Vibrotactile onbody feedback is better interpretable on the foot than on the wrist or waist, due to the higher resolution for haptic perception at this body area.

H2: Vibrotactile onbody feedback will be better perceive-able on the insole than on top of the foot.

H3: Vibrotactile onbody feedback at the foot is equally perceivable while moving around or standing.

H4: Vibrotactile onbody feedback in comparison to a visual handheld device can significantly reduce visual load and thus reduces stress occurring during the task of navigation.

H5: Vibrotactile navigation systems, such as the one we proposed, can replace previous pathfinding systems.

Methodology

For our evaluation, we made use of three established methods [47] and measured:

- Quantitative data (Error-rates – recorded by the study leader)
- Quantitative user feedback (subjective rating: required concentration & perceived strength of vibration)
- Qualitative user feedback (post questioning)

Procedure

At the beginning of each test phase, the subjects have been briefly introduced to the prototypes and the four vibration stimuli (left, right, forward and back). After completion of the test, each test subjects was asked to fill out a questionnaire in which they had to state demographic data and rate subjectively the *perceived strength of vibration*, their *required level of concentration* and the *wearing comfort* of the prototype on a 11 – bipolar point Likert scale (from strong / high: +5, neutral: 0, to weak / low: -5). Due to the limited space in this paper, not all of these ratings are reported here but those instances that yielded interesting insights.

A qualitative interview followed after the test. Hereby, further details on the user experience such as positive feedback or problems, or requests and suggestions have been reported. The interview and observations have been internally discussed, but are not being presented here due to the limited space.

General Construction of the Apparatus

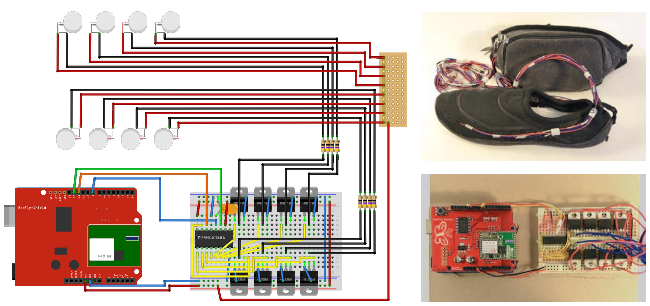

Figure 4. General Infrastructure of the Hardware Prototypes (*sketch by fritzing.org*).

We built five different prototypes (*see figure 1*): 2x Shoes, Sock Bandages, Wristband and a Belt, which we will evaluate based on the stated hypothesis. We utilized 4–12 off-the-shelf vibration motors (ROB-08449, which provide 1G vibration at 12,000 rpm at 3V), which were controlled by an Arduino Uno (*see figure 4*). The hardware (breadboard, Arduino+Wireless shield and a battery) had to be carried in a bumbag by the participants. In a Wizard of Oz style, the vibration signals were triggered wirelessly (OSC protocol) via a smartphone by the study leader.

STUDY 1: EVALUATING BODY POSITIONS (H1)

As we could learn from literature, there have already been made investigations on vibrotactile feedback for the purpose of navigation. In this study, we want to answer which position is most suitable for perceiving vibrotactile feedback for a path finding task while the user is walking.

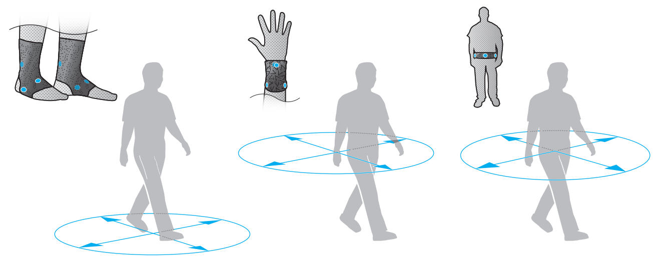

Figure 5. Four vibration motors were attached at each of the three body positions. Each vibration motor was assigned to a specific direction; therefore, the left vibration motor indicates the user to turn left.

We selected three positions common in literature:

a) Foot (Shoe/Sock): highest resolution of haptic perception – Deetjen et al. [9]

b) Wrist (Wristband): most reliable body part of vibrotactile sensation – Karuei et al. [18]

c) Waist (Belt): most frequently used position of vibrotactile feedback for navigation/directional tasks – [8,13,38,39]

Figure 6. The implementation of our prototypes: sock bandages, wristband, belt (white). Since our prototype is mobile, the hardware had to be worn in a black bumbag. Even though the wrist is the most agile body part of these, we did not dynamically adjust the vibrations in respect to the wrist's orientation.

We neither did pursue the concept of a handheld device, since it possibly prevents the user to take part in peripheral real world tasks; nor that of jewelry, because the implementation is unrealistic for a current product. Moreover, we also did not consider vibrations at the hand, because we do not want to disable the user from using their hands for different real world tasks. Due to the low social acceptance, we also did not use alternatives such as gloves.

The prototypes (*see figure 6*) were basically consisting of 4 vibration motors (VM), in which each is being assigned to a specific direction; VM 1: left, VM2: right, VM3: back, VM4: forward. To evaluate a suitable position for the vibration motors, we conducted a pilot study with 3 participants, in which we could confirm the minimum distances (*see figure 3*) that are necessary to distinguish differences on the surface of the skin. Taking this into consideration, we further evaluated the position on the stated *wearing comfort* and a *subjectively good felt distinctness*. We found out that the vibration motor on the back had to be adjusted a bit left from the spine to lie tightly at the body in order to be perceived.

To exclude an adaptation effect, the prototypes have been tested by 24 users in a between subject study. Hence, each user did only test one prototype.

- Group A – Foot: 8 users (2 females, 6 males) aged between 24 and 72 years (Ø 37 years)
- Group B – Wrist: 8 users (4 females, 4 males) aged between 25 and 70 years (Ø 35 years)
- Group C – Waist: 8 users (3 females, 5 males) aged between 24 and 72 years (Ø 44 years)

To reduce the influence of external factors, this first study took place in a lab-like environment. Each user was exposed to 13 direction changes in which the user had to state the perceived direction change resulting from the vibration. All users of each group received the same stimuli at different positions, which were (A) both feet, (B) right wrist and the (C) waist.

Results

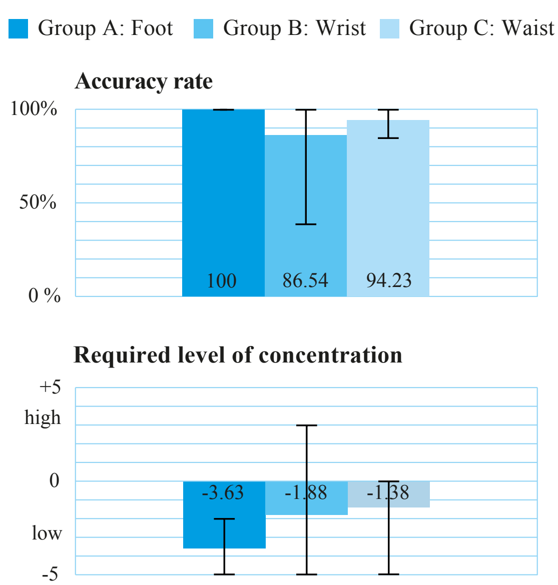

Figure 7. Performance comparison of three positions. (Error bars show the extreme values)

Accuracy rate. Due to the signal distribution of both feet, all users wearing the foot interface did not misinterpret any of the provided directional signals. However, a one-way ANOVA did not show any significant differences in terms of accuracy across all devices ($F_{2,21}$ = 2.12; p>.05).

Required level of concentration. Running a Kruskal-Wallis Test (k=3) indicated none of the ratings to be statistically significant (H_2=1.05; p=0.59) due to the small sample size. However, an F-Test presented a significantly high variance between Group A (M=-3.625; SD=1.302) & B (M=-1.875; SD=3.399) ($F_{7,7}$=16.43; p=.01) and between A & C (M=-1.375; SD=3.739) ($F_{7,7}$=8.24; p=.006), which indeed indicates a difference in rating.

In conclusion, every 104 vibration signals have been successfully identified without any errors for the foot interface. Even though both diagrams (see *figure 7*) indicate that the users perceived the vibrotactile feedback slightly better at the foot than on the other parts of the body that we tested, the foot interface did not yield a better statistically significant performance. We cannot absolutely support the findings of Karuei et al. [18], who figured the wrist and spine to be able to perceive vibrations more reliably than the foot. Furthermore, Karuei et al. reported that walking significantly reduces the odds of detecting a vibration. However, in their conducted experiments, the participants were walking on a treadmill, which on the one hand leads to an unnatural walking style and on the other hand interferes with the experiment through additional vibrations from the treadmill itself. Another explanation for the occurred disparity is that Karuei et al. only attached a single vibration motor to the top of the foot – we put four vibration motors tightly on different spots of the foot instead.

STUDY 2: ACTUATOR LAYOUT (H2)

Based on our previous findings and the fact that the foot has more sensing cells than the other tested positions, we decided to focus on the foot and did a literature review about vibrotactile foot interfaces accordingly. Velázquez et al. [41] proposed a shoe sole in which the vibration motors are arranged in a matrix layout to stimulate the foot sole. Furthermore, they proposed wave-like vibration patterns (*see figure 8*), which could be used for giving directions. Other approaches, such as from Karuei et al. [18], attach vibration motors on the top of the foot.

Here we wanted to evaluate whether Velázquez et al. insole matrix approach performs better than vibration on top of the foot, while we were using the approach of wave-like vibration patterns, in accordance to Israr & Poupyrev [16].

The participants (7 males, aged between 19 and 45 years, Ø 28 years) tested both prototypes in a within subject study:

- Prototype A (*figure 8 & 9 top*): Insole, Matrix-Layout with 12 vibration motors (similar to Velázquez et al. [42])
- Prototype B (*figure 8 & 9 bottom*): Shoe, 8 vibration motors were attached to the inside of the shoe wall.

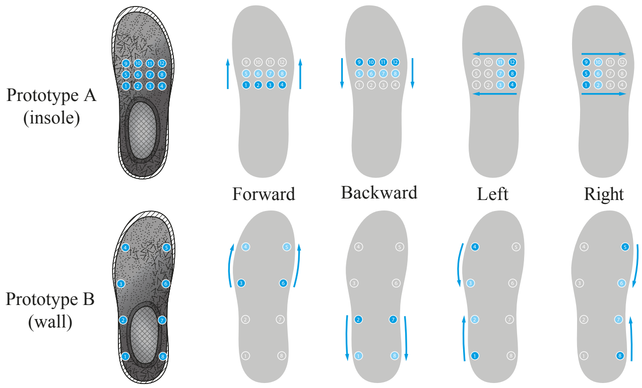

Figure 8. The participants were at first introduced to the signal patterns, which were different for each prototype, as indicated in this figure.

While the participants were standing, 4 (transitioning) vibration patterns were executed (*see figure 8*) and the participants were asked to interpret the pattern.

Each test subject was exposed to fourteen vibration patterns, which indicated directions: 1. back, 2. right, 3. left, 4. forward, 5. back 6. left, 7. right, 8. forward, 9. left, 10. back, 11. forward, 12. right, 13. back and 14. forward. The response of the test subjects to the perceived vibration pattern was indicated by turning in the appropriate direction and also through an oral response from the user. The study leader was evaluating the performance through recording the error rates.

Figure 9. Prototype A: upper pictures – insole matrix. Prototype B: middle bottom picture – actuators at the shoe wall. The different levels of pressure between body and actuators have been compensated with elastic rubber caps.

Results

It has been shown that the accuracy of correctly identified directional changes dropped quite a lot in this test; prototype A (*M*=68.36; *SD*=27.92) and prototype B (*M*=58.16; *SD*=27.79). We believe this to be caused by the wave-like vibration patterns, since Velázquez et al. [41,42] reported similar accuracy rates for these kinds of vibration patterns. Arranging the actuators underneath the feet achieved slightly higher accuracy (+10.2%), which was however found out not to be statistically significant via a t-Test (p=.5). Therefore, we cannot say that arranging the actuators in a small matrix underneath the feet does provide better feedback than distributed vibration motors on top of the foot. Even though the foot sole has more sensing cells than the topside, the dry and thick cornea makes a very precise sensation rather difficult. Having sensation underneath the foot sole, a designer must take into consideration that some people do not touch the whole insole when they hyperpronate [12]. Attaching the vibration motors on top of the foot requires the vibration motors to also touch the foot, which is more easily provided with sock-style prototypes.

STUDY 3: WALKING SPEED & PRECURSOR SIGNAL (H3)

Due to the results of our second study and the mentioned general drawbacks of having feedback underneath the foot, we decided to proceed with the second vibration layout and to forfeit wave-like vibration patterns due to their low performance (*figure 10*).

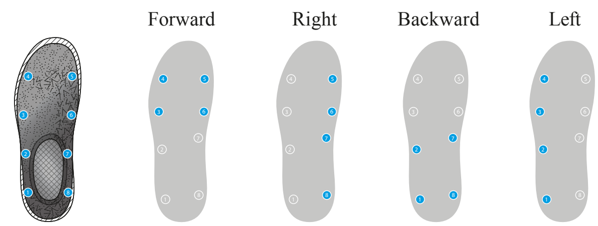

Figure 10. In blue indicated spots show the active vibration motors actuating at the same time.

In the previous test, participants stated to have had problems identifying the wave-like pattern, because they were surprised of the suddenly occurring vibration, which, as already mentioned, requires a lot of concentration. We wanted to investigate this issue and added a precursor signal (a 600ms long vibration), while the participants had to increase their speed level from standing to walking and jogging. The users were given again directional changes as mentioned above. To avoid having a learning effect between both conditions, we once more conducted a between subject study with 16 participants. Each group only tested one condition, while walking a distance of 50 meters on a lawn. The test was repeated for three different speed levels from standing, normal walking (~3km/h) and jogging (~5km/h).

- Group A: **vibration pattern** [vibration (600ms) – no vibration (150ms) – vibration (600ms)]
  8 users (2 female, 6 males) aged between 27 and 52 years (Ø 37.5 years)
- Group B: **precursor signal** [vibration (600ms) – no vibration (1000ms)] - **vibration pattern** [vibration (600ms) – no vibration (150ms) – vibration (600ms)]
  8 users (3 female, 5 males) aged between 24 and 50 years (Ø 34 years)

Results

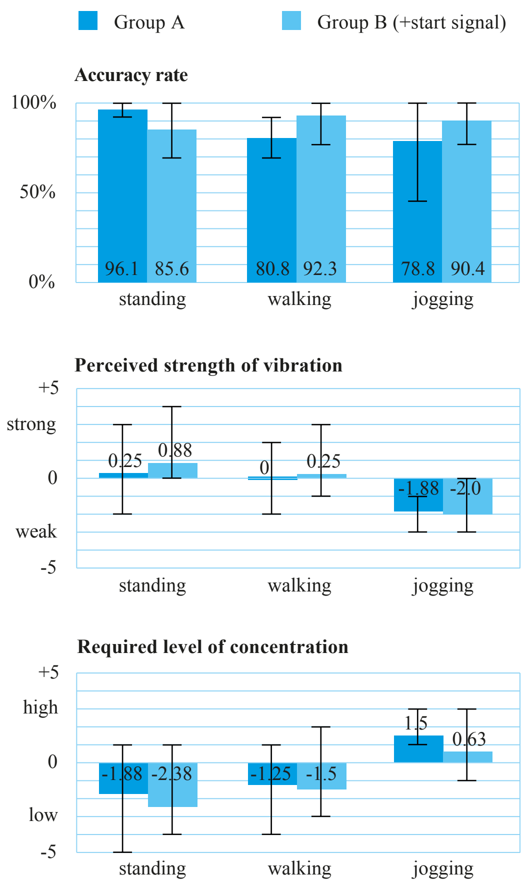

Figure 11. The influence of a precursor signal in comparison to the change of speed. (Error bars show the extreme values)

Accuracy rate. Compared to the previous test, the accuracy rate dramatically increased again, which confirms our assumption that the wave-like vibration patterns should not be deployed.

The difference between both conditions was confirmed to be statistically different by pairwise t-Tests (*see figure 11*). While standing (p<.05), Group A (M=96.15; SD=5.85) was producing less error rates than Group B (M=85.62; SD=12.3). While walking, the accuracy rate of the first condition, tested by Group A (M=80.8; SD=10.84) surprisingly dropped below the second condition with the precursor signal (M=92.3; SD=10.07), which was also found (out) to be statistically different (p<.05). While jogging, the difference between Group A (M=78.85; SD=19.15) and Group B (M=90.38; SD=9.85) minimized, so that a statistical difference could not be confirmed (p=.15). However, a one-way ANOVA and a Tukey HSD Test ($F_{2,21}$=4.15; p<.05) could confirm the increasing speed to significantly decrease the accuracy between standing and jogging for Group A. However, once the users in Group B got to know the precursor signal, this described negative effect did not appear that strongly anymore.

Perceived strength of vibration. A Friedmann Test (k=3) confirmed a significant difference in perception of the strength of vibration, depending on postures ($\chi^2(2)$=13, p=.0015). A pairwise Wilcoxon signed-rank test with Bonferroni Correction suggests that the vibrotactile perception while jogging is significantly harder to perceive than while walking (p<.05) and standing (p<.05). No statistical differences were found between walking and standing (p>.05). Furthermore, the additional precursor signal did not change the subjective perception of the strength of vibration, which was confirmed by a Mann Whitney test that showed no significant difference (p=.7).

Required level of concentration. Respectively to the perceived strength of vibration, the required level of concentration raised accordingly. A Friedmann Test (k=3) confirmed a significant difference for the required level of concentration depending on postures ($\chi^2(2)$=10.75, p=.0046). A pairwise Wilcoxon signed-rank test with Bonferroni Correction suggests that vibrotactile perception while jogging required significantly more concentration than while walking (p<.05) and standing (p<.05). Any differences between both groups could not be found to be statistically significant by a Mann Whitney test (p=.8).

STUDY 4: STRESS TEST – VIBROTACTILE VS. VISUAL FEEDBACK (H4)

In this study, we wanted to investigate the capability of vibrotactile feedback to possibly reduce stress for the purpose of pedestrian navigation. A similar experiment has been conducted by Bial et al. [3] with vibrotactile motorbike gloves while cycling. Their qualitative results reveal that vibrotactile feedback is preferred in combination with visual feedback, but not alone. In this study, we aimed at finding quantitative performance differences while generating an artificial stress situation. We more or less simulated situations in which the user is focused on a different task, such as reading/writing a message, walking through a crowded pedestrian precinct or focusing on a pedestrian running in front. We provided the user with pictures (*see figure 12*), in which the user had to find and count the correct letters (*odd-man-out* task).

Figure 12. Left: The odd-man-out tasks – counting the correct ”B” letters. Right: Group B had to visually focus on the smartphone for direction changes.

While the user had the task to walk straight until perceiving a direction change, the user also had to follow the direction change, which was either provided by A: vibration patterns at the foot with the sock prototype, or via B: visual feedback while using a handheld smartphone in landscape-mode. The direction changes occurred constantly after a while within a time frame of 7 seconds. To make performance differences between vibrotactile and visual feedback easier to measure, we measured the 1) *Accuracy rate* (navigation), 2) *Number of completed tasks*, and 3) *Correctly solved tasks*.

To avoid the user being biased, we conducted a between subject study with 18 participants in total:

- Group A – Vibrotactile: 9 users (1 female, 8 males) aged between 24 and 36 years (Ø 30 years)
- Group B – Visual: 9 users (4 females, 5 males) aged between 24 and 72 years (Ø 36 years)

Results

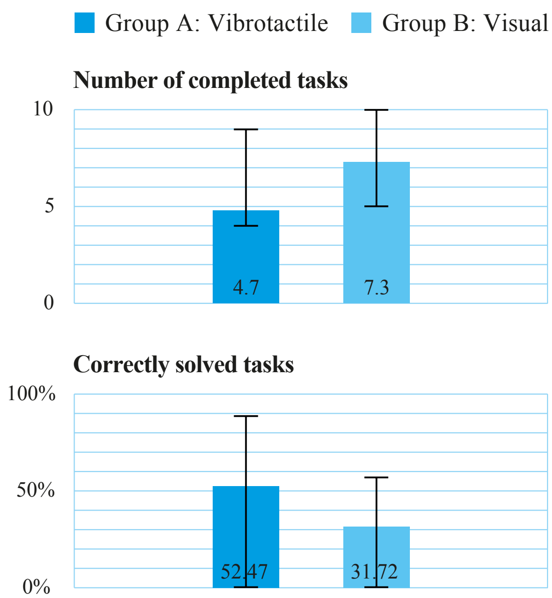

Figure 13. Vibrotactile vs. Visual Feedback. Even though Group B solved almost double the tasks, in average Group B solved 2.3 and Group A solved 2.4 tasks correctly. (Error bars show the extreme values)

Accuracy rate (navigation). Only 1 out of 117 direction changes have been erroneously identified at the vibrotactile feedback condition (99.14%). The visual feedback group made 3 mistakes (97.43%), which indicates no statistical difference in comparison to vibrotactile feedback (p=.5).

Number of completed tasks. A t-Test showed a significant difference in terms of completed tasks (p=.02). The Group B (M=7.3; SD=2.29) completed significantly more tasks than Group A (M=4.7; SD=1.98;).

Correctly solved tasks. While Group A (M=52.47) could almost solve significantly (p=.065) more of the completed tasks correctly than Group B (M=31.72), an F-Test found a statistically high variance ($F_{1,16}$=3.44; p=.49) between Group A (SD=33.72) and Group B (SD=18.2).

Participants of both groups stated to have been irritated when direction changes were indicated. Therefore, they had to start the *odd-man-out* counting task all over again, as reported. While performing the study, we could clearly recognize that the users with visual feedback seemed to be much more in a rush and were thus able to complete significantly more tasks than the vibrotactile group. These users stated to have often lost (their) focus on the sheet due to the frequent switching back to the smartphone display. This split attention might be the cause for the high error rate of this group. As a matter of fact, the visual feedback group did not solve more tasks correctly (Ø 2.3) than the vibrotactile feedback group (Ø 2.4).

STUDY 5: IN-SITU FIELD STUDY – STAND ALONE (H5)

Since our system was proposed to help the user to navigate through unknown environments, it is also needed to evaluate the feasibility of our system out in the field. To really gather valuable insights, we selected 3 experts (2 males and 1 female aged between 34–38 years) to test our system and provide us with unique qualitative feedback. The participants had a professional background (for at least 8 years) in the field of navigation or space and design.

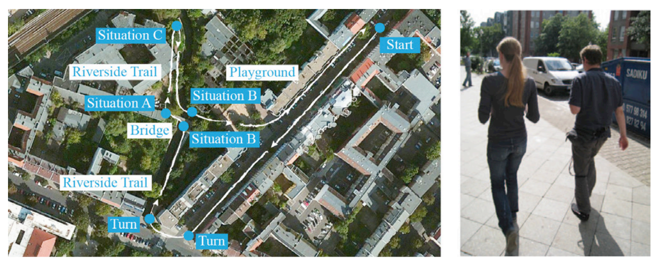

Figure 14. We provided 7 stimuli, which the user had to interpret. A study leader was logging the users' qualitative feedback on paper and a camera followed the study to track possibly appearing issues.

All participants were wearing the shoe prototype from study 3 (*stimuli: see figure 10*), while walking a certain route which was ~ 650 meters long. We chose the route to be quite heterogeneous with different ground surfaces (e.g. paving stone, asphalt, wooden planks and sand), while the user had to cross a bridge, roads and a playground.

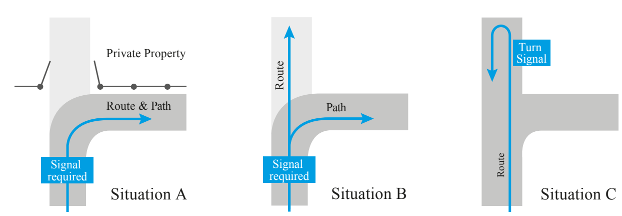

Figure 15. We encountered 3 situations, in which the user was provided with feedback.

Three different situations occurred (*see Figure 15*), in which the user was provided with a signal. Situation A was most obvious to the user, since it was very unlikely that the system would give the command to enter a private property. Situation B was more complicated, since the system would either provide a forward or a turn signal. In Situation C, the user was provided with a repeating turn pattern to turn back.

Results

Even though different surfaces could possibly create imagined vibrations, the users did not perceive "ghost vibrations" or missed them either. Overall, the tests were very productive; the experts pointed out many problems, which were not considered before:

- The request to continue walking straight was often not identified. In such cases, the user was asking for a repetition of the vibration pattern. To generally overcome this problem, a forward pattern should be unique, such as triple vibrations of all motors.
- The experiment showed that users tend to follow the path direction, even if there is another way transposed. We suggest running a vibration pattern for each change of ground surface.
- Contrary to our assumption, Situation A was prone to error when we did not give any vibrations at all. It occurred that the user was walking straight into the private land and believed to have reached his/her destination. Hence, a) for Situation A (see *figure 15*), a signal has also to be emitted and b), a certain vibration pattern should indicate when the user reached her desired destination.
- The directional statement for returning should only be given after a crossing (*figure 15: Situation C*) or at straight lane. Giving the statement before an intersection could lead to possible misunderstandings (e.g. turn left/right).
- All experts agreed that the system works stunningly well, but probably not sufficiently for a stand-alone assistance, since urban environments can be very ambiguous and situations such as Situation A (Figure 15) can occure quickly, which make decisions very difficult without more detailed hints.

SUMMARY

Comparing common approaches did not reveal the foot to perform best in perceiving vibro-feedback while walking

We cannot confirm **H1** with our first study, even though we learned that vibrotactile feedback at the foot has been interpreted with a higher accuracy than at the wrist or waist while walking in space. In contrast to the other interfaces, all study participants reported the foot to require less concentration with a significant lower variation.

No significant difference of perception between the top of the foot and the insole

H2 could not be verified as correct in our tests. In Study 2, the feedback underneath the foot did not yield significant improvements to the vibrotactile feedback on top of the foot. However, we could perceive that attaching vibration motors very close to the skin has an important influence on the recognition.

Increasing walking speed influences the accuracy negatively

That vibrotactile feedback is equally perceivable at different speed levels could not be confirmed with Study 3, and therefore **H3** needs to be rejected. Higher speed levels showed users to perceive the strength of vibration less, which caused higher concentration in return. However, our investigation indicates that – even though perception drops with higher speed – the accuracy is still sufficient to suggest using this setup for navigation while walking.

Relying on vibrotactile feedback instead of visual feedback potentially influences the level of stress

In our fourth study, we could perceive that users with visual feedback seemed to be much more stressed, which is indicated by the significantly higher number of completed tasks and the significantly higher error rate they produced. Having vibrotactile feedback on the foot had a positive effect and significantly reduced the error rate, while the user was not hectically solving the task. Thus, we confirm **H4**, vibrotactile feedback at the foot does reduce stress and the needed visual attention for the purpose of pedestrian navigation.

A directional system for pedestrian navigation in cities cannot only rely on vibrotactile feedback

At last, we conducted an in-situ field study with experts in which we encountered several weaknesses of a vibrotactile pedestrian navigation system. When it comes to navigating in unknown territory, visual hints, such as a map, are required to deal with ambiguous situations that one encounters in the city. Therefore, we reject **H5.** Experts unanimously suggested using vibrotactile assistance complementary to existing guiding solutions. However, training trails might improve the user experience.

CONCLUSION AND FUTURE WORK

In this paper, we described the design and an evaluation of vibrotactile onbody feedback at different areas of the body. Here, the foot provided the most promising results for the recognition of vibration patterns while walking in space. We determined that the user's walking speed affects the vibro-tactile perception, but not massively and is thus still being operable for its intended use. A pedestrian navigation system based on simple vibrotactile feedback for guidance might not be sufficient in an urban context with complex geographical situations. Further research is needed to either provide an extended "language" for vibrotactile clues to cover more complex geographical situations, or alternatively to explore how such vibrotactile clues can be integrated into multimodal navigation systems. Our studies indicated that vibrotactile feedback is potentially able to reduce stress of certain visual multitasks while navigating as a pedestrian. While such vibrotactile systems may not yet stand on their own, we believe that they can complement current modalities very well. However, according to literature there are certain scenarios in which vibrotactile navigation systems seem to be able to be used on their own, such as while driving a car [40] or a motorcycle [31] or when being on a boat [39], because these environments are mostly homogeneous or clear to the user.

Our research indicates that the foot is an interesting position for perceiving feedback, since the haptic channel is not occupied yet and potentially enables eyes-free and hands-free interaction. With the raising trend of wearable computing, onbody feedback will soon be an integral part of everyday wearables. Besides vibrotactile feedback, we should also think of utilizing different feedback modalities to stimulate other senses through pressure, heat, cold, and small electric shocks on the skin, which can provide unique sensations. On top of this, it might be interesting to investigate what kind of feedback modalities are being preferred (similar to Roumen et al. [34]), and whether there are statistical differences between genders.

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REFERENCES

1. Badju, A., Knorn, J., Lundberg, D., Sjöberg N. (2013) Navibration. Avancerad Interaktionsdesign, MAMN01, Lund Tekniska University. URL: *http://vimeo.com/81807456*
2. Bellik, Y., & Farcy, R. (2002). Comparison of various interface modalities for a locomotion assistance device. In *Computers Helping People with Special Needs.* 421-428. Springer Berlin Heidelberg.
3. Bial, D., Kern, D., Alt, F., & Schmidt, A. (2011). Enhancing outdoor navigation systems through vibrotactile feedback. *In CHI'11 Extended Abstracts on Human Factors in Computing Systems* (pp. 1273-1278). ACM.
4. Brewster, S., & Brown, L. M. (2004, January). Tactons: structured tactile messages for non-visual information display. In *Proceedings of the fifth conference on Australasian user interface.* Volume 28 (pp. 15-23). Australian Computer Society, Inc.
5. Brock, A., Kammoun, S., Macé, M., & Jouffrais, C. (2014). Using wrist vibrations to guide hand movement and whole body navigation. In *i-com*, 13(3), (pp. 19-35).
6. Choi, S., & Kuchenbecker, K. J. (2013). Vibrotactile display: Perception, technology, and applications. In *Proceedings of the IEEE,* 101(9), 2093-2104.
7. Cholewiak, R. W., Collins, A. A., & Brill, J. C. (2001, July). Spatial factors in vibrotactile pattern perception. In *Proceedings of Eurohaptics Conference.*
8. Cosgun, A., Sisbot, E. A., & Christensen, H. I. (2014) Guidance for Human Navigation using a Vibro-Tactile Belt Interface and Robot-like Motion Planning. *Georgia Institute of Technology, Atlanta, GA.*
9. Deetjen, P., Speckmann, E. J., & Hescheler, J. (2005). Repetitorium Physiologie. *Urban & Fischer*.
10. EARSandEYES (2014) Handy im Straßenverkehr: Jüngere unterschätzen das Risiko. *Ears and Eyes Creating new Grounds*. URL: http://www.earsandeyes.com/en/presse/handy-im-strassenverkehr/?pdf=1
11. Frey, M. (2007). CabBoots: shoes with integrated guidance system. In *Proceedings of the 1st international conference on Tangible and embedded interaction* (pp. 245-246). ACM.
12. Gould, N. (1983). Evaluation of hyperpronation and pes planus in adults. In *Clinical orthopaedics and related research*, 181, 37-45.
13. Heuten, W., Henze, N., Boll, S., & Pielot, M. (2008). Tactile wayfinder: a non-visual support system for wayfinding. In *Proceedings of the 5th Nordic conference on Human-computer interaction: building bridges* (pp. 172-181). ACM.
14. Hornecker, E., Swindells, S., & Dunlop, M. (2011). A mobile guide for serendipitous exploration of cities. In *Proceedings of the 13th International Conference on Human Computer Interaction with Mobile Devices and Services* (pp. 557-562). ACM.
15. IDEO (2001). Technojewelry - Concepts for wearable technology. URL: *http://www.ideo.com/work/technojewelry*
16. Israr, A., & Poupyrev, I. (2011). Tactile brush: drawing on skin with a tactile grid display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 2019-2028). ACM.
17. Kammoun, S., Jouffrais, C., Guerreiro, T., Nicolau, H., & Jorge, J. (2012). Guiding blind people with haptic feedback. In *Frontiers in Accessibility for Pervasive Computing (Pervasive 2012).*
18. Karuei, I., MacLean, K. E., Foley-Fisher, Z., MacKenzie, R., Koch, S., & El-Zohairy, M. (2011). Detecting vibrations across the body in mobile contexts. In *Proceedings of the SIGCHI conference on Human factors in computing systems* (pp. 3267-3276). ACM.
19. Kojima, Y., Hashimoto, Y., Fukushima, S., & Kajimoto, H. (2009). Pull-navi: a novel tactile navigation interface by pulling the ears. In *ACM SIGGRAPH 2009 Emerging Technologies* (p. 19). ACM.
20. Labiale, G. (1990). In-car road information: Comparisons of auditory and visual presentations. In *Proceedings of the Human Factors and Ergonomics Society Annual Meeting* (Vol. 34, No. 9). pp. 623-627). SAGE Publications.

21. Liu, Y. C. (2001). Comparative study of the effects of auditory, visual and multimodality displays on drivers' performance in advanced traveller information systems. In *Ergonomics*, 44(4), 425-442.

22. Locke, M. (1984). Epidermal cells. In *Biology of the Integument* (pp. 502-522). Springer Berlin Heidelberg.

23. Madden, M., Rainie, L. (2010). Adults and cellphone distractions. URL: *http://pewinternet.org/~/media//Files/Reports/2010/PIP_Cell_Distractions.pdf*

24. Matthies, D. J. C., Müller, F., Anthes, C., & Kranzlmüller, D. (2013). ShoeSoleSense: proof of concept for a wearable foot interface for virtual and real environments. In *Proceedings of the 19th ACM Symposium on Virtual Reality Software and Technology* (pp. 93-96). ACM.

25. Meier, A. (2014). Orientieren mit allen Sinnen — Multisensorische Wahrnehmung und Orientierung am Beispiel vibro-taktiler Fußgängernavigation. *Master's Thesis. University of Applied Sciences Potsdam (FHP).*

26. Nørretranders, T. (1998). The User Illusion: Cutting Consciousness Down to Size, trans. Jonathan Sydenham. *New York: Viking Penguin*.

27. Panëels, S., Brunet, L., & Strachan, S. (2013). Strike a Pose: Directional Cueing on the Wrist and the Effect of Orientation. In *Haptic and Audio Interaction Design.* 117-126. Springer Berlin Heidelberg.

28. Pielot, M., & Boll, S. (2010). Tactile Wayfinder: comparison of tactile waypoint navigation with commercial pedestrian navigation systems. In *Pervasive computing* (pp. 76-93). Springer Berlin Heidelberg.

29. Pielot, M., Poppinga, B., & Boll, S. (2010). PocketNavigator: vibro-tactile waypoint navigation for everyday mobile devices. In *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services* (pp. 423-426). ACM.

30. Pielot, M., Poppinga, B., Heuten, W., & Boll, S. (2012). Tacticycle: Supporting exploratory bicycle trips. In *Proceedings of the 14th international conference on Human-computer interaction with mobile devices and services* (pp. 369-378). ACM.

31. Prasad, M., Taele, P., Goldberg, D., & Hammond, T. A. (2014, April). Haptimoto: Turn-by-turn haptic route guidance interface for motorcyclists. In *Proceedings of the 32nd annual ACM conference on Human factors in computing systems*. 3597-3606. ACM.

32. Robinson, S., Jones, M., Eslambolchilar, P., Murray-Smith, R., & Lindborg, M. (2010, September). I did it my way: moving away from the tyranny of turn-by-turn pedestrian navigation. In *Proceedings of the 12th international conference on Human computer interaction with mobile devices and services*. 341-344. ACM.

33. Rekimoto, J. (2013). Traxion: a tactile interaction device with virtual force sensation. In *Proceedings of the 26th annual ACM symposium on User interface software and technology* (pp. 427-432). ACM.

34. Roumen, T., Perrault, S.T., Zhao, S. (2015) NotiRing: A Comparative Study of Notification Channels for Wearable Interactive Rings. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*. ACM.

35. Rümelin, S., Rukzio, E., & Hardy, R. (2011). NaviRadar: a novel tactile information display for pedestrian navigation. In *Proceedings of the 24th annual ACM symposium on User interface software and technology* (pp. 293-302). ACM.

36. Steltenpohl, H., & Bouwer, A. (2013). Vibrobelt: tactile navigation support for cyclists. In *Proceedings of the 2013 international conference on Intelligent user interfaces*. 417-426. ACM.

37. Poppinga, B., Pielot, M., & Boll, S. (2009). Tacticycle: a tactile display for supporting tourists on a bicycle trip. In *Proceedings of the 11th International Conference on Human-Computer Interaction with Mobile Devices and Services* (p. 41). ACM.

38. Tsukada, K., & Yasumura, M. (2004). Activebelt: Belt-type wearable tactile display for directional navigation. In *UbiComp 2004: Ubiquitous Computing* (pp. 384-399). Springer Berlin Heidelberg.

39. Van Erp, J. B., Van Veen, H. A., Jansen, C., & Dobbins, T. (2005). Waypoint navigation with a vibrotactile waist belt. In *ACM Transactions on Applied Perception (TAP)*, 2(2), 106-117.

40. Van Erp, J. B., & Van Veen, H. A. (2004). Vibrotactile in-vehicle navigation system. In *Transportation Research Part F: Traffic Psychology and Behaviour*, 7(4), 247-256.

41. Velãzquez, R., Bazán, O., & Magaa, M. (2009). A shoe-integrated tactile display for directional navigation. In *International Conference on Intelligent Robots and Systems, IROS*. (pp. 1235-1240). IEEE.

42. Velázquez, R., Bazán, O., Varona, J., Delgado-Mata, C., & Gutiérrez, C. A. (2012). Insights into the Capabilities of Tactile-Foot Perception. In *International Journal of Advanced Robotic Systems*, 9.

43. Weber, B., Schatzle, S., Hulin, T., Preusche, C., & Deml, B. (2011). Evaluation of a vibrotactile feedback device for spatial guidance. In *World Haptics Conference (WHC)*. 349-354. IEEE.

44. Wickens, C. D. (2002). Multiple resources and performance prediction. *Theoretical issues in ergonomics science,* 3(2), 159-177.

45. Zeichner, N., Perry, P., Sita, M., Barbera, L., Nering, T. (2014) Exploring HowMobile Technologies Impact Pedestrian Safety. NYC Media Lab Research Brief.

46. Zöllner, M., Huber, S., Jetter, H. C., & Reiterer, H. (2011). NAVI–A proof-of-concept of a mobile navigational aid for visually impaired based on the microsoft kinect. In *Proceedings of INTERACT.* 584-587. Springer Berlin Heidelberg.

47. Zühlke, D. (2012). Nutzergerechte Entwicklung von Mensch-Maschine-Systemen: *Useware-Engineering für technische Systeme*, Vol2. Springer Berlin Heidelberg.