# Studying the User Experience with a Multimodal Pedestrian Navigation Assistant

Gustavo Rovelo[1,2], Francisco Abad[3] and M.C.-Juan[3] and Emilio Camahort[3]
[1] *Expertise Centre for Digital Media, Hasselt University, Wetenschapspark 2, Diepenbeek, Belgium*
[2] *Dpto. de Sistemas Informáticos y Computación*
[3] *Instistuto Universitario de Automática e Informática Industrial*
*Universitat Politcnica de Valncia, Camino de Vera S/N, Valencia, Spain*
*gurorui@posgrado.upv.es, {fjabad, mcarmen, camahort}@dsic.upv.es*

Keywords: Multimodal Interface, User Evaluation, Mobile Augmented Reality

Abstract: The widespread usage of mobile devices together with their computational capabilities enables the implementation of novel interaction techniques to improve user performance in traditional mobile applications. Navigation assistance is an important area in the mobile domain, and probably Google Maps is the most popular example. This type of applications is highly demanding for user's attention, especially in the visual channel. Tactile and auditory feedback have been studied as alternatives to visual feedback for navigation assistance to reduce this dependency. However, there is still room for improvement and more research is needed to understand, for example, how the three feedback modalities complement each other, especially with the appearance of new technology such as smart watches and new displays such as Google Glass. The goal of our work is to study how the user perceives multimodal feedback when their route is augmented with directional cues. Our results show that tactile guidance cues produced the worst user performance, both objectively and subjectively. Participants reported that vibration patterns were hard to decode. However, tactile feedback was a unobtrusive technique to inform participants when to look to the mobile screen or listen to the spoken directions. The results show that combining feedback modalities produces good user performance.

## 1 INTRODUCTION

Smartphones combine, among other features, a high resolution display with multitouch capabilities, different tracking sensors, permanent Internet connection and good processing power. The widespread usage of these devices has created new opportunities for Human-Computer Interaction researchers (HCI), developing novel types of applications and interaction techniques. One of the main challenges in this area is that smartphones are used, most of the time, in highly demanding environments for users' attention, especially when they are on the move (Jameson, 2002; Oulasvirta et al., 2005). For that reason, developing mobile applications that implement efficient user interaction is very important. In particular, pedestrian navigation assistants have to (1) provide robust guiding cues and (2) avoid distracting users from keeping an eye on the road or socially interact with friends.

Different studies in this particular application domain have investigated how to use auditory, tactile and visual cues to improve how pedestrians receive navigation assistance (Liljedahl et al., 2012; Pielot and Boll, 2010). Multimodal feedback offers many benefits in this regard: eyes-free operation, language independence, faster decision-making, and reduced cognitive load (Jacob et al., 2011b). Multimodal feedback is also appreciated by the users (Pielot et al., 2012b): complementary tactile feedback was used in one third of the logged routes where users had the option to receive only visual feedback on a digital map similar to Google Maps. However, as also mentioned in many of those works, there is still room for analysis of the properties of multimodal feedback and thus, improvement of the mobile interfaces.

The main contribution of our work is to study the scenario where visual directional cues are presented using the smartphone's screen as a video see-through display, where the user can observe both the surroundings and the visual feedback. We build our multi-

To appear in Proceedings of the International Conference on Computer Graphics Theory and Applications (GRAPP) 2015, March 11th - 14th, Berlin, Germany
http://www.grapp.visigrapp.org/

modal guidance system upon the findings of previous research, and evaluate how using the augmented view of the path to provide visual directional cues affects the experience and performance of the user in our mobile application.

Visual direction cues were presented as virtual arrows or paths superimposed on the rear camera feed, showing an augmented view of the path as depicted by Figure 1. Auditory and tactile direction cues were presented as spoken directions and vibration patterns, respectively. Based on the results of (Vainio, 2009), we designed our system to provide continuous rhythmic feedback to guide the user in the navigation task.

Figure 1: Visual directional cues augment the video feed of the rear camera on the smartphone's display, letting the user perceive both the environment and the guidance at the same time.

We invited a group of volunteers to complete a predefined route in our university, a semi-controlled environment where they could safely perform the task while still being immersed in a realistic scenario. The results of the statistical analysis show that vibration patterns produced the worst results when used alone: participants needed more time completing the route and in general, decoding directions. However, when this feedback was combined with auditory or visual modalities it produced better results. Participants mentioned that vibrations indicated them when to put more attention to the auditory directions or when to observe the smartphone's screen. On the other hand, auditory and visual feedback produced good results both alone and combined. These modalities were more intuitive. However, participants reported that the sun glares made it difficult to read on-screen messages and the noise level in the environment affected hearing the auditory directional cues.

## 2 RELATED RESEARCH

Previous research has presented different navigation prototypes that use vibrotactile output devices to provide directional information to pedestrians. For example using a belt with 6 tactors (tactile actuators) to provide navigation assistance (Pielot et al., 2009). It resulted more efficient for following the route from point A to point B than map-based navigation.

In NaviRadar (Rümelin et al., 2011) the system provided different vibration patterns using an external device connected via bluetooth to a mobile phone. The user received feedback when an automatic radar sweeping mechanism crossed the area containing the direction to follow. This approach produced effective results, as participants could follow the directional cues easily.

Continuous tactile feedback produced good results guiding pedestrian navigation in the Pocket Navigator system (Pielot et al., 2010). The user receives vibrotactile feedback when pointing the mobile phone in the right direction and helped participants to complete the required route successfully.

Using tactile feedback to indicate the direction to follow without forcing the user to complete a predefined route to reach a specific destination is another approach studied in the past (Robinson et al., 2010). Even when they did not find statistically significant differences with respect to the base line condition, the results of the tactile feedback were slightly better.

Tactile feedback has also been combined with visual feedback (Jacob et al., 2011a; Jacob et al., 2011b): using a colour code, i.e. green, orange and red; to indicate the required navigation task (continue with the route, scan for new direction, and error in route) and vibrations that indicate the direction to follow. Our experiment proposes a less abstract representation of visual directional cues, augmenting the view of the route with virtual graphical directions. We expect the AR view to improve on the code-based directions, as it provides a live view of the surroundings of the user. As shown in (Chittaro and Burigat, 2005), arrows displayed on top of pictures of the route provide efficient guidance.

Tactile navigation has also been combined with auditory feedback for navigation tasks such as sightseeing (Magnusson et al., 2010; Szymczak et al., 2012). In this case, vibrotactile feedback was efficiently used to guide tourists, while auditory feedback provided information about the points of interest close to the user.

On the other hand, different variations of auditory feedback have been proposed as navigation aids. For example, using spatial sound as guiding feedback, asking the user to scan the environment to find the new direction, moving the audio source from one ear plug to another, and increasing the intensity when the user points the device in the right direction (Liljedahl and Papworth, 2012). However, this approach requires the user wearing headphones that can isolate users from their surroundings, for example, interfering with the conversation with another person. A similar approach is used in "gpsTunes" (Strachan et al., 2005). That system proposes to use changes in the volume of music, increasing it when the user comes closer to the desired place. Their results show that these auditory cues can help users complete navigation tasks successfully.

All the different approaches have proved to some extent the benefits of tactile and auditory feedback to complement or replace visual navigation aids. However, there are open questions regarding how the three feedback modalities can be used together; especially with the increasing processing power of mobile computing platforms and wearable devices that can present visual feedback without distracting the user's attention.

# 3 Experiment Description

We evaluated the effect of multimodal feedback for pedestrian navigation assistance guided by the following research questions:

- How useful is visual feedback—the augmented view—to provide directional cues? This type of feedback typically requires to deviate visual attention from the path to the screen and can also be affected by visibility problems, caused for example by sun glares.
- How useful is auditory feedback? In a real-world situation, this type of feedback can be missed because of noise. However it also represents an intuitive way to give direction cues, and can be used when vision is not available.
- How useful and intuitive is tactile feedback to provide direction cues?
- Does the combination of feedback modalities improve user performance?

During the experiment, we gathered subjective information from participants about their experience using the application through questionnaires and interviews. The questionnaires included yes/no, open, multiple choice and Likert scale questions (from 1 to 5, the lowest and the highest score for each question respectively).

The questionnaire included a general section for every participant in the experiment, but it also included specific questions regarding visual, auditory and tactile feedback for those participants that completed the path receiving them. We also quantified participants' performance according to:

- Time to complete the route ($T$): Time required to complete the route, from the moment the participant chooses the destination, to the confirmation of the end-of-route signal.
- Time to confirm the reception of the end-of-route signal ($T_e$): Time a participant takes to acknowledge the end of route signal.
- Average number of missed checkpoints ($N_{mc}$): Number of times a participant missed a checkpoint where she was supposed to turn. We define a checkpoint as a place on the path where the participant has to make a decision: turn left or right, keep walking straight ahead, or confirm the arrival at the destination. A checkpoint is considered missed when the participant reaches the checkpoint but does not turn as indicated and continues walking in the wrong direction. We set the threshold distance to 5 meters from the geographical coordinate of the checkpoint.

## 3.1 Methodology

Every participant in the experiment started the trial reading the written instructions about how to interpret the information given by the application. They also filled out a questionnaire with their demographics. After that, and before starting to follow the path, a member of our team confirmed that the instructions were understood, and gave some final explanation when it was required. Participants were also instructed about the purpose of the experiment: follow the directions provided by the system as accurately as possible. They were kindly asked not to stop during the trial for any reason that was not related to the experiment, such as talking to a friend.

Participants were also explicitly instructed to keep the phone pointing along their way to avoid noise in the above measurements. We did not observe any miss-pointing problems and we did not have to discard any sample.

When they were ready to start, participants had to select the destination from a menu option. In this case, there was only one available destination to choose from. Then, participants had to start the route, followed by one member of our team from an approximate distance of 5 meters. No interventions were required during the whole experiment.

When participants reached the destination point at the main entrance of one of the university buildings, they had to touch the screen of the smartphone two times—two taps—in order to confirm the reception of the end-of-route message. After completing the path, participants answered a written questionnaire regarding their experience.

Our application is able to show visual elements either in portrait or landscape modes. However, we performed a pilot experiment with members of our research institute to evaluate both layouts. The 10 participants of the pilot experiment preferred holding the smartphone horizontally, in landscape mode. One of the comments was that "the text and the rest of the content was better viewed this way". For this reason, we modified the application to only show the content in landscape mode, and not responding to the smartphone's orientation changes.

We performed the experiment with first year students during their first month at the university. We did not mention the destination building to avoid biasing the results. We also performed the experiments during class hours, to avoid revealing the route in advance to participants before they performed the experiment.

Participants were randomly assigned to one of the following groups, determining what combination of feedback they received during the experiment:

**Group 1 (A)** Auditory feedback only.

**Group 2 (T)** Tactile feedback only.

**Group 3 (V)** Visual feedback only.

**Group 4 (AT)** Auditory and tactile feedback.

**Group 5 (AV)** Auditory and visual feedback.

**Group 6 (TV)** Tactile and visual feedback.

**Group 7 (ATV)** Auditory, tactile and visual feedback.

## 3.2 Participants

There were 77 participants in our experiment, 54 men and 23 women. All of them first year university students. They were between 17 and 24 years old ($19.03 \pm 1.71$ in average). Only 11 participants (14.29%) had used an AR application before; 31 participants (40.26%) had used a GPS before, and 23 participants (29.87%) owned a smartphone.

## 3.3 Apparatus

After evaluating the available options for developing AR mobile applications, we decided to develop our pedestrian navigation assistant for a smartphone running Android OS. The application has the same basic purpose as a commercial GPS system: providing direction cues to reach a desired destination, but with subtle differences that are explained in this section.

We used the digital compass, the GPS and the built-in camera of a smartphone with a microprocessor running at 1GHz. It has a 3.7″ display ($480 \times 800$ pixels resolution), a 5 MP rear camera that is able to record video at 24 fps at a maximum resolution of $640 \times 480$ pixels.

We constructed a virtual map of one portion of the university and designed a path to follow during our experiment. It is 155 m long, and it has 6 checkpoints where the system provides direction cues: 3 left turns, 2 right turns, and the destination point. We carefully chose the path to avoid zones which may cause tracking issues because of buildings or trees blocking the GPS signal. Figure 2 shows the map of the route. The path can lead to 7 possible buildings, and there are different alternative routes to follow from start to end.

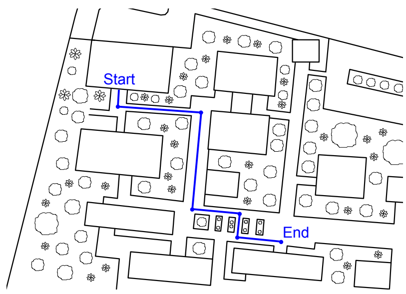

Figure 2: The route every participant followed.

Battery consumption was not an issue for our purposes, hence the screen was turned on during the entire experiment, we collected GPS data every 200 ms and set the request of orientation data with the SENSOR_DELAY_FASTEST constant, which, as described by the official Android SDK documentation, makes the application to get sensor data as fast as possible.

The standard interface of the application includes four basic elements: the video stream from the mobile phone's camera, the application menu (on demand), the destination and a distance to destination labels. These elements are always visible, regardless of the feedback combination under evaluation.

During the execution, the application can be in one of four states: *(i)* the participant points the mobile in the right direction, *(ii)* the participant has to turn, *(iii)* the participant has missed a *checkpoint* and has to go back, and *(iv)* the participant has reached the final destination.

For example, consider the following scenario: when the participant approaches a point where she has to turn left, the application passes from *state 1* to *state*

*2*; if she misses the turn, and keeps walking, there is a transition *to state 3*. When the participant walks back pointing the mobile phone in the direction of the checkpoint, there is a transition to *state 1*, and when the missed checkpoint is reached, *state 2* is activated again to point the participant in the right direction. Finally, when the participant reaches the destination, the system presents a message and stops providing feedback. The following sections describe the different types of feedback provided during the experiment.

#### 3.3.1 Visual Feedback

To enhance the system described in (Chittaro and Burigat, 2005), when visual feedback is active, the participant is presented with these elements: a virtual path drawn on the camera's view when the participant points the mobile phone in the right direction towards the next checkpoint, an arrow pointing to the correct direction when the participant has to turn or has deviated from the right path, and a radar image that codes direction and distance to target. Figure 1 depicts the visual elements of the interface when the user is pointing the mobile phone in the right direction.

When the subject completes the path and reaches the desired destination, a visual signal is shown on the screen to indicate that the task has finished.

We employed OpenGL ES to draw the virtual elements of our application on top of the camera's video feed.

#### 3.3.2 Auditory Feedback

Auditory feedback presents navigation cues as any commercial GPS device does. In the first state, a synthetic voice informs the participant to continue in that direction: "Walk straight ahead". When the participant has to turn left or right, the synthetic voice indicates so: "Turn left" or "Turn right". When the participant has missed a checkpoint, the synthetic voice indicates so: "You missed a checkpoint and you need to go back". Finally, when the participant reaches the final point in the path, the voice utters the message: "You have reached your destination".

Each one of the voice directions is repeated once, when a state change occurs. However, participants could ask for the repetition of the last message selecting an option from the menu. We used the Text-To-Speech features of the Android library to generate the voice instructions.

#### 3.3.3 Tactile Feedback

Tactile feedback is provided by means of the vibrator of the mobile phone using the magic wand metaphor (Fröhlich et al., 2011), that requires the participant pointing the mobile phone in the right direction to receive the directional information. This metaphor has been used before in way finding tasks with good results (Pielot et al., 2012a; Raisamo et al., 2012).

We follow a similar approach to the one proposed by (Raisamo et al., 2012), changing the vibration pattern at a checkpoint to attract participant's attention. Our system also required participants to turn the phone scanning the space around them to find the new direction. Our system uses the following vibration patterns: when the participant is on the right path, a repetition of 0.5 s vibration pulses separated by 1 s periods with no vibration; an approaching change in direction is represented as a sequence of 0.5 s vibration, 0.3 s with no vibration, 0.5 s vibration and 1 s with no vibration; when the destination is reached, three 0.5 s vibration pulses, separated by 0.3 s with no vibration as a confirmation, and then the application stops producing feedback.

# 4 Statistical Analysis

To analyse the results of the questionnaires, we used the Kruskal-Wallis Rank Sum test to compare the effect of feedback modality on the response of the participants to Likert scale questions and the Wilcoxon rank sum test with continuity correction to compare the effect of gender, previous experience using a GPS on the response of the participants to Likert scale questions.

Shapiro-Wilk test of normality and Bartlett Test of Homogeneity of Variances showed that our data did not fulfil ANOVA prerequisites. Therefore, we used data transformation techniques to be able to use parametric tests in the analysis of the performance measures. In this section we use the * mark to highlight statistically significant differences with $p < 0.05$ and the ** statistically significant differences with $p < 0.01$.

## 4.1 Questionnaires and Interviews

When asked how much participants liked the application, 59 out of the 77 (76.62%) chose the level 5 in the Likert scale; 15 (19.48%) chose level 4, and 3 (3.90%) participants chose level 3. Neither the Kruskal-Wallis Rank Sum of Feedback modality nor the Wilcoxon rank sum test with continuity correction for Gender and Previous Experience using a GPS showed any statistically significant effect on the degree to which participants liked or disliked our application.

Regarding how easy to use the application was, 52 participants (67.53%) rated it with a 5 in the Likert scale; 9 participants (11.69%) with a 4, 11 participants (14.29%) with a 3, 4 participants (5.19%) with a 2 and only one participant (1.30%) with a 1. In this case, only the Gender factor had a statistically significant effect on the easiness level (Wilcoxon rank sum test with continuity correction $W = 452.5$, $p = 0.02$). Women rated the easiness level with a median of 4 ($IQR = 2$) in the Likert scale, while men rated the easiness of using the application with a median of 5 ($IQR = 0$).

The sun glares caused problems when reading the messages on the screen for 41 participants (53.25%). We should take into account that even participants of groups without visual feedback had the distance to target and the destination labels on the screen. None of the factors we analysed had a statistically significant effect on the number of participants that reported problems with sun glares. On the other hand, all the participants believed that using more than one feedback modality would improve the effectiveness of the system.

None of the participants that completed the path receiving auditory feedback (A, AT, AV or ATV groups) considered it annoying. They also reported having all the information they needed to complete the route. The frequency of auditory feedback was appropriate for 37 of the 44 participants (84.09%). However, none of the factors under analysis present statistically significant differences. Auditory feedback usefulness was rated with the highest score by 30 of the 44 participants (68.18%); 7 participants (15.91%) chose level 4 in the Likert scale; 5 participants (11.36%) chose level 3 and only 2 participants (4.55%) rated it with a 2. The volume of auditory feedback was a problem for 6 participants, who mentioned that the voice was too low (even when the smartphone speaker was set at its maximum level). Another comment made by a participant was that listening to the auditory feedback was boring, because it was too repetitive.

Participants that completed the route receiving tactile feedback (T, AT, TV and ATV groups) mentioned that it was not annoying. However, tactile feedback was not enough to receive guiding information for 39 out of the 44 participants (88.63%). Only 5 participants (from the ATV group) mentioned that it was enough. Regarding the frequency of the tactile feedback, 39 out of the 44 participants (88.63%) considered it appropriate. The other 5 participants belong to one of the multimodal groups (AT, TV and ATV). The perceived usefulness was lower for tactile feedback: 20 participants out of 44 (45.46%) rated it with a 1 in the Likert scale; 11 participants (25%) with 2, 7 participants (15.91%) rated it with 3, 5 participants (11.36%) with 4 and only one participant (2.27%) with the highest score, 5 in the Likert scale. This last participant belonged to the ATV group.

Comments about tactile feedback were more varied: 3 participants mentioned that the vibration frequency was too slow. On the other hand, 2 participants gave positive comments about tactile feedback, mentioning that it keeps you alert on your route. They remarked tactile alerts combined with auditory and visual feedback made the application very useful.

Finally, 43 out of 44 participants that completed the path with visual feedback mentioned it was not annoying. The only participant that thought otherwise belonged to the TV group. Only 4 participants (9.09%) mentioned they felt they needed more information for completing the route. On the other hand, 37 participants (84.09%) reported that the frequency of the feedback was appropriate. Regarding the usefulness of Visual feedback to provide the guiding information, 28 participants (63.64%) rated it with the highest score in the Likert scale; 8 participants (18.18%) rated it with a 4; 6 participants (13.64%) with a 3; one participant rated it with a 2, and one participant rated visual feedback with the lowest value of the Likert scale. Sun glares caused 37 participants (84.09%) to report trouble and discomfort reading the on-screen messages. Combining visual with auditory and tactile feedback was mentioned as a good alternative for this situations.

The easiness to follow the instructions to complete the route was rated with a 5 in the Likert scale by 57 participants (74.03%). It was rated with a 4 by 10 participants (12.99%), with a 3 by 4 participants (5.19%); with 2 by 5 participants (6.49%), and with the lowest rate by one participant only (1.30%). Participants that considered it was somehow difficult belonged to A, V, TV and ATV groups. The participant that considered it very difficult belonged to AV group.

## 4.2 Performance Results

The Multifactor ANOVA reveals that only the Feedback modality factor has a statistically significant effect on Time to complete the route ($T$) with a large effect size ($F(6,70) = 13.52$, $p = 1.0 \times 10^{-3}$**, *partial* $\eta^2 = 0.609$). There is no statistically significant interaction among any of the factors under analysis with respect to $T$.

The Tukey HSD post-hoc analysis for Feedback modality factor and $T$ revealed statistically significant differences between tactile feedback and the rest of the groups. Figure 3 shows the average and standard deviation $T$ for every feedback group.

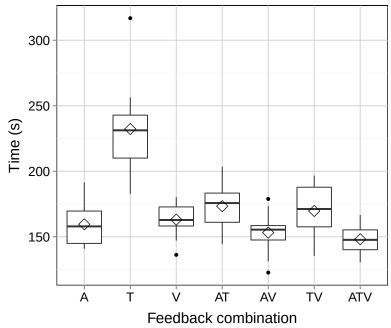


Figure 3: Time to complete the route box plot ($T$).

The Multifactor ANOVA did not show any statistically significant differences regarding the Time to confirm the reception of the end-of-route message. Finally, no participant missed a checkpoint, and thus, there was no data to compare the Average number of missed checkpoints.

## 5 Discussion

Visual and auditory feedback were the most intuitive way to receive navigation assistance for participants in our experiment. Spoken directions and the visual elements mixed with the video feed of the smartphones' camera are both promising ways to provide navigational cues to the user. Especially if we consider the fact that wearable devices such as Google Glass provides the necessary hardware to reduce the visibility and hearing problems reported in our experiment.

Our results align with what has been reported by previous studies (Jacob et al., 2011b; Magnusson et al., 2010; Szymczak et al., 2012): multimodal feedback improves user performance. Participants in our experiment mentioned that receiving a different vibration pattern at a checkpoint increased their awareness of the decision point, efficiently attracting their attention to the smartphone screen or the spoken directional cues. Participants mentioned that tactile and auditory feedback helped them to keep focus on the route.

On the other hand, the fact that we considered in our design the precision of commercial GPS systems, including a radius of 5 m around the checkpoints to provide feedback, caused that none of the participants missed a checkpoint during the experiment. This highlights the importance of timing in pedestrian navigation assistance, because even when participants receiving only tactile feedback required more time to complete the route, all the participants were able to complete the itinerary.

Participants mentioned that sun glares made it difficult to observe and read the on-screen messages, and that the volume of auditory feedback was not high enough (even when the volume of the smartphone was set at its maximum level). This problem highlights the importance of a careful design considering the context in which feedback is going to be used. For example, auditory feedback would not be appropriate in contexts as a library or a museum.

## 6 Conclusions and Future Work

Visual and auditory feedback produced better results, both from the subjective appreciation of the participants and also regarding the performance measures. In our approach, the augmented view provided similar information than a commercial GPS, but with the advantage of showing the real environment instead of just a map, while auditory feedback provided spoken instructions about the direction to follow. Tactile feedback is the least effective way to provide directional cues, which is not surprising, as previous research found similar results when tactile feedback was compared to traditional GPS systems feedback (Pielot and Boll, 2010). However, according to the user experience, tactile feedback is helpful to alert the user about an approaching decision point in the route, and also as an alternative when visual or auditory feedback are not available.

We plan to take our application one step further, and repeat the experiment using an wearable devices, such as Google Glass and the Samsung Smart watch, to evaluate the user experience and to study how multimodal feedback can be used to improve pedestrian navigation assistants.

## Acknowledgements


This research has been funded by the National Council of Science and Technology of México as part of the Special Program of Science and Technology and by grant ALFI-3D, TIN2009-14103-C03-03 of the Spanish Ministry of Science and Innovation.


## REFERENCES


Chittaro, L. and Burigat, S. (2005). Augmenting Audio Messages with Visual Directions in Mobile

Guides: An Evaluation of Three Approaches. In *Proc. of the 7th Int. Conf. on Human Computer Interaction with Mobile Devices and Services*, MobileHCI, pages 107–114.

Fröhlich, P., Oulasvirta, A., Baldauf, M., and Nurminen, A. (2011). On the Move, Wirelessly Connected to the World. *Com. of the ACM*, 54(1):132–138.

Jacob, R., Mooney, P., Corcoran, P., and Winstanley, A. C. (2011a). Guided by Touch: Tactile Pedestrian Navigation. In *Proc. of the GIS Research UK 19th Annual Conf.*, GISRUK, pages 205–215.

Jacob, R., Mooney, P., and Winstanley, A. C. (2011b). Guided by Touch: Tactile Pedestrian Navigation. In *Proc. of the 1st Int. Workshop on Mobile Location-based Service*, MLBS, pages 11–20.

Jameson, A. (2002). Usability Issues and Methods for Mobile Multimodal Systems. In *Proc. of the ISCA Tutorial and Research Workshop on Multi-Modal Dialogue in Mobile Environments*.

Liljedahl, M., Lindberg, S., Delsing, K., Polojärvi, M., Saloranta, T., and Alakärppä, I. (2012). Testing Two Tools for Multimodal Navigation. *Adv. in Human-Computer Interaction*, 2012.

Liljedahl, M. and Papworth, N. (2012). Using Sound to Enhance Users' Experiences of Mobile Applications. In *Proc. of the 7th Audio Mostly Conf.: A Conference on Interaction with Sound*, AM, pages 24–31.

Magnusson, C., Molina, M., Rassmus-Gröhn, K., and Szymczak, D. (2010). Pointing for Non-visual Orientation and Navigation. In *Proc. of the 6th Nordic Conf. on Human-Computer Interaction: Extending Boundaries*, NordiCHI, pages 735–738.

Oulasvirta, A., Tamminen, S., Roto, V., and Kuorelahti, J. (2005). Interaction in 4-second bursts: The fragmented nature of attentional resources in mobile hci. In *Proc. of the SIGCHI Conf. on Human Factors in Computing Systems*, CHI, pages 919–928.

Pielot, M. and Boll, S. (2010). Tactile Wayfinder: Comparison of Tactile Waypoint Navigation with Commercial Pedestrian Navigation Systems. In *Proc. of the Int. Conf. on Pervasive Computing*, Pervasive, pages 76–93.

Pielot, M., Henze, N., and Boll, S. (2009). Supporting Map-based Wayfinding with Tactile Cues. In *Proc. of the 11th Int. Conf. on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI, pages 23:1–23:10.

Pielot, M., Heuten, W., Zerhusen, S., and Boll, S. (2012a). Dude, Where's My Car?: In-situ Evaluation of a Tactile Car Finder. In *Proc. of the 7th Nordic Conf. on Human-Computer Interaction: Making Sense Through Design*, NordiCHI, pages 166–169.

Pielot, M., Poppinga, B., and Boll, S. (2010). Pocketnavigator: vibro-tactile waypoint navigation for everyday mobile devices. In *Proc of the Conf. on Human-Computer Interaction with Mobile Devices and Services*, Mobile HCI, pages 423–426.

Pielot, M., Poppinga, B., Heuten, W., and Boll, S. (2012b). PocketNavigator: Studying Tactile Navigation Systems In-situ. In *Proc. of the SIGCHI Conf. on Human Factors in Computing Systems*, CHI, pages 3131–3140.

Raisamo, R., Nukarinen, T., Pystynen, J., Mäkinen, E., and Kildal, J. (2012). Orientation Inquiry: A New Haptic Interaction Technique for Non-visual Pedestrian Navigation. In *Proc. of the 2012 Int. Conf. on Haptics: Perception, Devices, Mobility, and Communication - Volume Part II*, EuroHaptics, pages 139–144.

Robinson, S., Jones, M., Eslambolchilar, P., Murray-Smith, R., and Lindborg, M. (2010). "I Did It My Way": Moving Away from the Tyranny of Turn-by-turn Pedestrian Navigation. In *Proc. of the 12th Int. Conf. on Human Computer Interaction with Mobile Devices and Services*, MobileHCI, pages 341–344.

Rümelin, S., Rukzio, E., and Hardy, R. (2011). NaviRadar: A Novel Tactile Information Display for Pedestrian Navigation. In *Proc. of the 24th Annual ACM Symposium on User Interface Software and Technology*, UIST, pages 293–302.

Strachan, S., Eslambolchilar, P., Murray-Smith, R., Hughes, S., and O'Modhrain, S. (2005). GpsTunes: Controlling Navigation via Audio Feedback. In *Proc. of the 7th Int. Conf. on Human Computer Interaction with Mobile Devices and Services*, MobileHCI, pages 275–278.

Szymczak, D., Magnusson, C., and Rassmus-Gröhn, K. (2012). Guiding Tourists Through Haptic Interaction: Vibration Feedback in the Lund Time Machine. In *Proc. of the 2012 Int. Conf. on Haptics: Perception, Devices, Mobility, and Communication - Volume Part II*, EuroHaptics, pages 157–162.

Vainio, T. (2009). Exploring Multimodal Navigation Aids for Mobile Users. In *Proc. of the 12th IFIP TC 13 Int. Conf. on Human-Computer Interaction: Part I*, INTERACT, pages 853–865.