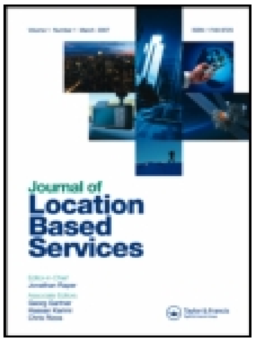

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# Pedestrian navigation with augmented reality, voice and digital map: final results from an *in situ* field study assessing performance and user experience

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This paper reports on a field study comparing navigation performance and user experience of voice, digital map and augmented reality (AR) interfaces for electronic assistance in the context of pedestrian navigation. The *in situ* study was conducted with two subsequent experiments in the city of Salzburg along a pre-defined route using a self-implemented smartphone application running on Apple's iPhone 4. The study involved 48 participants aged between 22 and 66 years with different experiences in using smartphones and navigation systems. Navigation performance was measured on a micro-level including information on effectiveness (number and reasons of stops, global positioning system (GPS accuracy), efficiency (walking and task completion time, duration of stops) and satisfaction (NASA Task Load Index, System Usability Scale). A final questionnaire completed the study. Between the first and the second experiment, the application was adapted considering user feedback and the previous findings. Results show that in the context of GPS-enhanced pedestrian navigation, digital map and voice-only interfaces lead to significantly better navigation performance and user experience in comparison to AR interfaces. The study also reveals similar results for digital map and voice-only interfaces given that voice instructions are carefully composed. Results lead to the conclusion that AR is still suffering from usability and hardware issues leading to higher uncertainty of navigating persons. Best navigation performance and user experience can be achieved by combining digital maps and accurate voice instructions.

**Keywords:** pedestrian navigation; *in situ* field study; augmented reality; voice; digital map

## 1. Introduction

Smartphone applications supporting people in everyday orientation and navigation tasks are becoming more and more popular. While early implementations primarily addressed the domain of car navigation, previous developments shift the focus to pedestrians, too (Arikawa, Konomi, and Ohnishi 2007). There are two main reasons for this trend: the permanent availability of smartphones as personal assistants and the technical equipment of smartphone devices with high-resolution touch displays, global positioning system (GPS) sensors, tilt sensors and magnetometers, being well suited for assisting personal orientation

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and wayfinding tasks. Following these trends, recent technical developments prepared the ground for complex smartphone-based navigation applications, mainly due to a steady demand for ubiquitous navigation support and sophisticated new navigation features.

Although smartphones are capable devices for realising personal navigation assistance, the question of effective communication of route knowledge remains. Over the last years, considerable research has been conducted on the evaluation of route communication issues, including the context of electronic navigation assistance. Studies have been concerned with (1) visual modalities (map-based, text-based, image-based, augmented reality (AR) overlay), (2) non-visual modalities (e.g. audio, tactile and haptic modes) and (3) arbitrary combinations of these basic kinds. Recent research shows that most studies either evaluate a particular user interface without direct comparisons to other modalities or combine more than one modality so that no conclusions for a single technology can be drawn. Thus, comparing navigation performance and user experience between the most common modalities such as digital map, AR display (which means overlaying digital navigation information on the user's smartphone camera view) and voice-only guidance is still considered as an open issue.

The aspect of electronic navigation assistance and the need for a comparative study design call for an in-depth field study aiming at comparable evaluation results for each single-user interface modality. To the authors' best knowledge, this is the first empirical study under nearly identical real-world conditions pursuing the goal of comparing different route communication modalities.

The remainder of the paper is structured as follows: the next section reviews related work. Section 3 describes the study design. Section 4 is concerned with the implementation of the three user interface modalities map, voice and AR as smartphone application for pedestrian navigation. Study results are discussed in Section 5. Section 6 draws conclusions and gives an outlook.

## 2. Related work

In the discussion of related work, we focus on empirical field studies assessing performance and user experience of electronic navigation support.

As maps have a long tradition in supporting personal navigation, focus of recent research has been on questions concerning adaptations of maps to electronic navigation systems (Baus, Cheverst, and Kray 2005). In related work, limitations concerning the small display size on mobile devices (Dillemuth 2005) as well as problems of users aligning 2D maps to the current surroundings (Liljedahl et al. 2012) were observed. Also, 3D maps do not lead to considerable improvements (Coors 2005). Text-based navigational concepts have been found to work basically well, but suffer from reading texts during walk. In contrast, Mulloni, Seichter, and Schmalstieg (2011) came to the conclusion that AR is mostly used during walks, especially in proximity of road intersections.

While the approach of advanced navigation visualisation modalities is not new (Narzt et al. 2005), smartphones and miniaturised sensor components (e.g. GPS, electronic compass and accelerometer) have become powerful enough for real-world usage in field studies. In accordance to the technical development, the enhancement of map-based systems by rendering virtual objects in real-time superimposing photographs or the phone's camera view has gained more and more attention (Erifiu and Ostermayer 2012). For instance, Beeharee and Steed (2006) demonstrated a combination of textual instructions, maps and geo-tagged photos. The exploratory study showed that with the image-based mode, test users finished the route significantly faster than with the map- and text-mode. However, participants were confused by pictures that were not taken exactly along the route. Hile et al. (2008) extended their work by automatically augmenting geo-tagged photos with 2D directional arrows. The result of mismatching photos to the real environment was confirmed in their exploratory study, too. Thus, the authors further enhanced their system by rendering several views of augmented images of landmarks with 3D directional arrows (Hile et al. 2010). Although the user study showed improvement in participants' satisfaction, the problem of not matching the current view of the user's current location remained. Also Walther-Franks and Malaka (2008) tested the usefulness and usability of photos augmented with visual navigation instructions in contrast to a commercial mobile 2D map application in pedestrian mode. Participants evaluated the augmented photograph-based system significantly better than the map-based system. Authors remark that the map-based system was north-oriented and therefore test persons had to turn their device in order to view the map in walking direction. Another interesting approach to this issue has been proposed by Ishikawa and Yamazaki (2009) who explored augmenting maps with street scene photographs. The authors compared the effectiveness of both displays for providing orientation at underground exits. In this study, participants also showed higher performance with photographs compared to maps. Furthermore, Mulloni, Seichter, and Schmalstieg (2011) investigated the user experience of a map interface combined with glyphs, text and audio instructions versus an arrow-based AR interface combined with textual instructions in an exploratory study. A key finding of their study is that participants with AR experience used the augmented view more often; other participants preferred the map view. In follow-up activities, Mulloni and Schmalstieg (2012) investigated three further AR-based interfaces: (1) an AR view with compass overlay, (2) a zooming panorama with compass overlay and (3) a satellite image augmented with text labels. Results of two user evaluations with 20 students reveal that the effectiveness of each interface depends on the specific (navigation) task. Also, Kluge and Asche (2012) studied, by means of informal eye-tracking, how often users rely on an AR mode or on a 2D map. Outcomes of the conducted experiment are consistent with the findings from Mulloni, Seichter, and Schmalstieg (2011) and Mulloni and Schmalstieg (2012) who also find that AR view is mainly used at complex decision points, typically before and after road intersections.

Driven by the need to reduce the load on visual attention as well as providing additional presentation modes for users with particular needs (e.g. vision-impaired persons), the interest in eyes-free modalities increased over the last years (Szymczak et al. 2012). Haptic output to deliver guidance to pedestrians (Bosman et al. 2003) and speech are the most common alternative approaches. The performance and user experience of haptic feedback has been successfully proven in previous studies (Heuten et al. 2008; Pielot and Boll 2010; Azenkot, Ladner, and Wobbrock 2011; Pielot et al. 2012). Jacob, Mooney, and Winstanley (2011) confirm the potential of haptic-enabled navigation applications as an alternative to purely visual or audio-based applications. Voice-only guidance for electronic pedestrian navigation has been investigated by Goodman, Brewster, and Gray (2005). The authors concluded that elderly people benefit from using an electronic navigation aid with spoken and/or written instructions. Nevertheless, they indicate that more research is necessary to compose high-quality voice instructions. This gap was closed with a series of studies addressing voice-only electronic navigation support (Rehrl et al. 2009; Rehrl, Häusler, and Leitinger 2010). The authors addressed several shortcomings of voice instructions in the context of electronic navigation support and proposed a method for using cognitively ergonomic turn instructions (Klippel, Richter, and Hansen 2009) in electronic pedestrian navigation assistance. A field study revealed that with a carefully composed instruction set, voice-only navigation is feasible at minimal error rate and standard walking times. Janarthanam et al. (2013) tested in the Spacebook project a speech-driven mobile dialogue app supporting pedestrians in navigation and gathering tourist information. Results showed that participants were facing orientation problems due to navigation instructions relying too much on street names or missing confirmatory indications for being on the right way.

An empirical field study assessing both visual and non-visual technologies has been carried out by Stark, Riebeck, and Kawalek (2007) who tested four different navigational concepts: (1) auditory instructions plus visual routing information on a map, (2) visual routing information on a map, (3) map-based visualisation with position and walking direction and (4) textual description by street name. The authors indicate that none of the concepts could be identified as the optimal one. Depending on the usage scenario, each of the concepts has its benefits. Nevertheless, results give hints on the best practices for interface design. Furthermore, Chittaro and Burigat (2005) presented an experimental evaluation comparing audio directions augmented with different types of visual information: (1) map, (2) combination of map and photographs and (3) combination of large arrows and photographs. In this case, users find their way faster if the map is augmented with photographs or completely replaced with photographs and arrows. However, the combination of map and photographs was highly preferred by test participants.

Summarising previous work, we conclude that there is no satisfying answer to the question, 'which impact on navigation performance and user experience comes from which interface mode?' While recent studies reveal better results for photograph-based navigation, the subjective rating for maps is typically better. Navigation performance in auditory mode is generally considered poor – although voice instructions are mainly used in addition to a map display or textual instructions – and not tested in voice-only settings. A study investigating voice-only guidance has been published (Rehrl, Häusler, and Leitinger 2010), but does not compare the results with other interface technologies. Also empirical field tests comparing an AR interface for everyday use in pedestrian navigation with other single interface modalities have not been carried out. Walther-Franks and Malaka (2008) argue that AR prototypes are typically too cumbersome and obtrusive to evaluate with potential users. The presented work closes the gap 'to get a trade-off between available equipment, participants and time need to be done in order to get a good understanding while keeping the evaluation manageable' (Szymczak et al. 2012, 336).

## 3. Methodology

The methodology of this work follows a user-centred design approach by applying the method of usability inquiry. Usability inquiry proposes to obtain likes, dislikes, needs and understanding of the system by talking to users, observing users, using the system in real-world scenarios or letting users answer questions (Zhang 2007). One of the methods used in usability inquiries are field observations (Nielsen 1993). Consequently, for studying navigation performance and user experience with different interface modalities in the context of a real-world pedestrian navigation task, we carried out two iterative field tests by using a self-implemented mobile application running on Apple's iPhone 4. The application is capable of switching between the three navigation modes: (1) multi-touch map interface, (2) voice-based interface and (3) AR interface. The decision for self-implementing the navigation application is mainly based on the needs coming from the research method of user experience prototyping: we improved the application after getting results and feedback from the first iteration, which can be best achieved by implementing the different interfaces in a way that any design decision could be revised and changed at any time. Beyond user field tests, the evaluation method of usability inquiry includes interviews and continuous logging of actual use (Nielsen 1993) which are described in detail in Section 3.4.

### 3.1 *Test route*

The test route for our study was situated in the inner city district of Salzburg, Austria. The whole route was 1800 m long and modelled with 27 decision points (a decision point is defined as a place where route following has to be assisted by navigation instructions due to multiple choices). To evaluate the three different user interface modalities, we split the route into three sub-routes, whereas each sub-route represents a different set of characteristics (Table 1 and Figure 1).

In order to get a comparable data-set, we did not change the route setting between the first and the second iteration.

### 3.2 *Test group selection*

We recruited a total of 48 participants, 24 females and 24 males (12 females and 12 males for each field experiment) who were grouped into three age classes: younger than 30 (age class 1), 30–60 (age class 2) and older than 60 (age class 3). The youngest person was 21 years, and the oldest was 73 years. The mean age of participants for the first iteration was $M = 39.55$ (SD = 14.91) and $M = 42.24$ (SD = 17.38) for the second iteration. We classified participants concerning their experience with smartphones in 'no experience', 'experienced with smartphones in general' and 'experienced with car and/or pedestrian navigation on smartphones'. None of the participants were familiar with the test route. In order to avoid any learning effects of participants between the first and the second iteration, a new group of participants was recruited for the second iteration. Therefore, it could be ensured that participants navigated for them unknown routes in each experiment.

### 3.3 *Experimental design*

The experimental setup is based on a within-participants design with using the method of counterbalancing (Dancey and Reidy 2011). The chosen design allows to systematically

Table 1. Characteristics of sub-routes.

| Sub-route | Length (m) | Decision points | Characteristics (according to Walther-Franks and Malaka 2008) |
|---|---|---|---|
| Sub-route 1 | 625 | 8 | Time to walk on average 8 min 23 s, road crossings, car traffic, far-spread decision points, straight stretches, open places with traffic |
| Sub-route 2 | 695 | 10 | Time to walk on average 10 min 20 s, densely set decision points, traffic lights, road crossings, car traffic |
| Sub-route 3 | 480 | 9 | Time to walk on average 6 min 15 s, stretches with many subsequent turns, stretches along narrow streets, busy stretches (tourist area), pedestrian zones, bus traffic at the end of the sub-route |


Figure 1. Test route divided into three sub-routes (SR1, SR2, SR3).

Table 2. Within-participants design with counterbalancing.

| All participants ($N = 24$) | Sub-route 1 | Sub-route 2 | Sub-route 3 |
|---|---|---|---|
| Eight participants | Augmented reality | Voice | Digital map |
| Eight participants | Voice | Digital map | Augmented reality |
| Eight participants | Digital map | Augmented reality | Voice |

vary the modality sequences – based on the criteria mentioned in the section before – due to which participants completed each sub-route with each of the three modalities (Table 2).

## 3.4 *Measures*

In order to gather detailed insights on navigation performance, we collected detailed measures on a micro-level for an in-depth analysis of participants' behaviours including information about:

(1) *Effectiveness*: number of stops (and reasons for stops), GPS accuracy.
(2) *Efficiency*: walking time, task completion time, duration of stops ($\geq 1$ s).
(3) *Satisfaction*: NASA Task Load Index (TLX; Hart and Staveland 1988).

Before the experiment, the standardised Santa Barbara Sense-of-Direction Scale (SBSDS) (Hegarty et al. 2002) was applied to measure the scale of environmental spatial ability of the participants (see Section 5.1). Finally, participants rated the usability of the tested navigation modalities with the SUS – system usability scale (Brooke 1996) (see Section 5.5). It is a proved and reliable test to assess the usability of a given device or software by determining the three dimensions satisfaction, efficiency and effectiveness by asking participants to rate 10 Likert-scaled items.

### 3.5 *Conducting the evaluation*

Experiments of the first iteration were carried out between September and November 2010, and between May and July 2011 for the second iteration. All experiments took place between 08:30 and 18:00 (depending on weather and daylight conditions) with each experiment lasting between 70 and 90 min. Participants were accompanied by two supervisors staying the same for each iteration. One supervisor was observing the test runs and guiding through the interviews; the other supervisor was collecting the quantitative data as well as data about the qualitative performance.

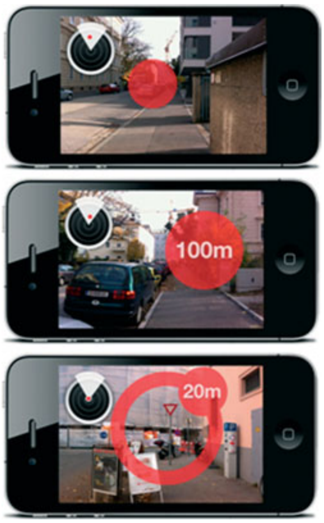
At the beginning of a test session, each participant completed the SBSDS. Before starting a sub-route, the participant was asked to complete a training session in order to become familiar with the test setting and to gain (first) experiences with the particular technology. The short training routes, requiring navigation along two decision points, were spatially separated from the main route used in the experiment. With this approach, we aimed at avoiding biased results coming from unfamiliar smartphone handling or interaction problems with the user interface.

After this brief training session, the test persons were led to the pre-defined starting point of the first sub-route. The navigation system was switched to one of the three interface modalities, following a pre-defined plan (see Section 3.3). The task for the participants was to navigate to the end of the pre-defined route; the smartphone application was designed in a way that no route handling was necessary on behalf of the users (Walther-Franks and Malaka 2008). If participants made a wrong decision at a decision point, the supervisor used gestures to indicate the right choice. No other assistance was given during navigation. In order to avoid any influence on participants, the supervisor followed participants several meters behind and recorded observations with a voice recorder. When reaching the end point of a sub-route, supervisors asked participants questions concerning spatial knowledge, usability and task load. After completing one sub-route, the interface was switched to the next modality and the same procedure was repeated for the next sub-route. When finishing the experiment, participants were asked final questions to gather further qualitative feedback and user experiences. Finally, we rewarded participants with an amount of money as a token of appreciation.

## 4. Implementation

Participants were handed over an iPhone 4 application, running the three navigation modes (1) digital map, (2) voice and (3) AR, which are described in the following section. It introduces the chosen design approaches and implemented user interfaces for the first test iteration as well as the adaptions (according to our user-centred design approach) applied for the second test iteration.

(A)




AR interface of 1st iteration

(B)

AR interface of 2nd test iteration

Figure 2. Augmented reality interface with rendered overlay information in 2D design (A) and 3D design (B).

### 4.1 *AR view*

By using GPS, the magnetometer and tilt sensor, the AR view provided users with rendered route information augmenting the live picture of the iPhone camera view. The height of street geometries – coming from OpenStreetMap (OSM) – were pre-set to the height of the GPS signal (in order to avoid problems with height mismatches coming from distorted GPS signals). As suggested in related work (Kolbe 2003; Schmalstieg and Reitmayr 2007; Stark, Riebeck, and Kawalek 2007; Hile and Borriello 2008), we followed the approach of implicit route instructions. The idea of the so-called 'follow-me' principle is to annotate the camera view with some kind of virtual route path. As related work does not offer specific rendering suggestions, we rendered route information for the first iteration as 2D graphics without any perspective distortion. As shown in Figure 2(A), our guidance used three different styles of graphical indicators, depending on the distance to a decision point:

- *100–60% distance*: semi-transparent circle, marking the position of the decision point,
- *60–30% distance*: circle with additional display of the remaining distance (in m),
- *Less than 30% distance*: indicator changed its appearance to a ring shape, enclosing the decision point to be entered; by enlarging the ring when approaching a decision point, users should get the feeling of crossing a portal.

Since the proposed AR user interface was evaluated significantly worse compared with the other modalities for the first test iteration, we decided to completely redesign the AR view with a 3D rendering (OpenGL) of a virtual route path. Users were able to navigate by simply following a virtual green bond on the ground as shown in Figure 2(B), independent of the remaining distance to the decision point. In contrast to the first prototype, which required a horizontal alignment of the iPhone, test persons of the second iteration could change the view between landscape and portrait mode according to their preferences. The additional vision/direction indicator in the upper left corner of the screen was changed from a red point in the first iteration to a green arrow displaying the correct walking direction as well as controlling the overall person's orientation. In both iterations, a vibration alarm was raised in case of reaching a decision point. Finally, for the second iteration, we used the same set of points of interest for all three modalities in order to provide the same information for all test users with each interface modality.

## 4.2 *Voice-only guidance*

The implementation of the voice-only guidance was based on a single screen with a slider for controlling the sound volume and a button to offer the possibility to repeat the latest voice instruction. Beyond considering the wayfinding choreme theory (Klippel et al. 2004) as well as findings of the previous studies (Klippel et al. 2004; Rehrl et al. 2009; Rehrl, Häusler, and Leitinger 2010), we followed the approach of extending topological route graphs with the concept of navigation activities, which are composed of a sequence of one to four qualitative spatial actions (Rehrl 2011). Each qualitative spatial action is composed of (1) an action verb (e.g. walk or turn), (2) an intrinsic (e.g. left, right) or extrinsic (e.g. across, in, to) spatial relation and (3) an optional spatial reference (e.g. a visible entity like a bridge or a prominent building). An example activity with a sequence of three actions is (1) 'Walk half left', (2) 'Walk in the direction of the hotel named "Villa Carlton"' and (3) 'Walk to the roundabout'. For automatically processing such activity graphs in order to generate voice instructions by the navigation application, it was decided to use the OSM database. The open data model of OSM allowed us to flexibly cast activity-graphs into the OSM data scheme. So, qualitative spatial actions could be transformed to textual instructions following the rules and standards of a schema-based approach of natural language generation (Reiter and Dale 1997). Finally, we generated voice commands out of textual instructions by means of an appropriately configured text-to-speech engine. For achieving realistic conditions, we used the built-in text-to-speech engine of iPhone 4. Appropriate configuration was achieved by empirically adjusting the text speed.

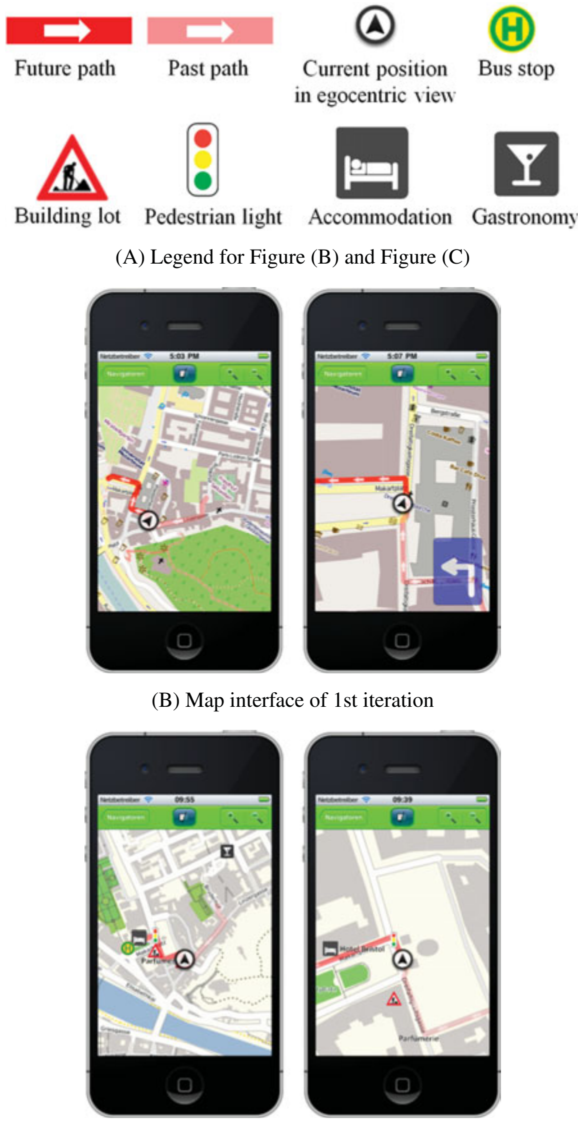
During the experiment, whenever a user came close to a decision point, the application indicated the approaching of a decision point with a vibration alarm and played the voice instruction describing the way from the current to the next decision point. As inaccurate GPS signals could lead to missing, too early or too late voice instructions, we compensated this shortcoming with the so-called 'sensitive areas'. Thus, the alarm's location was calculated by correlating the GPS position of the user (respectively that of the mobile device) with the sensitive area around the WGS84 coordinates of the decision point. For getting the best results, we selected 10–20 m as sensitive area around decision.

### 4.3 *Digital map*

For the map user interface, we considered four essential design goals based on the work of Agrawala and Stolte (2000): *readability* (all essential components, especially the roads, should be visible and easily identifiable), *clarity* (the route should be clearly marked and readily apparent from a quick glance), *completeness* (the map must provide all necessary information for navigation) and *convenience* (the map should be easy to carry and manipulate). Further literature (Gartner and Radoczky 2006; Gartner and Uhlirz 2005; Raubal and Panov 2009; Schmid et al. 2010) provided useful hints for route map design such as (1) providing an overview of the whole route at the beginning of the navigation task and also during route following, (2) automatic adaptation of the presented map section to the position of the user, (3) egocentric map view, (4) the route should be visible to the user at any time and (5) the distinction between the past and the future path should be unambiguous. Additionally, we considered suggestions from literature concerning generalisation, scale, extend and colours (Darken and Peterson 2001; Dillemuth 2005). Figure 3(B) shows the selected map user interface for the first iteration, whereas Figure 3(C) shows the adapted version for the second test iteration.

We visualised the route with a red line and a pattern of small white arrows pointing in the forward direction. To clearly separate the past and the future route at the current position, the two route sections were tinted differently. As suggested in related work, the already completed route part was displayed in the lower third of the screen, whereas the coming route part was rendered in the upper two-thirds of the screen. While user feedback in the first iteration was positive regarding the graphical visualisation of the route itself, results showed that participants were confused by the map interface concerning two main points. First, street names were partly not readable because of their wrong adjustment on the map (e.g. upside down). This problem occurred as the standard OSM tiles were used, and these map tiles are aligned to the north. To improve the readability of street names, for the second iteration, different map tiles for the four cardinal directions were rendered. By switching the map tiles according to the walking direction (determined with the electronic compass), an adjusted labelling of the street names could be achieved. A further improvement for the second iteration was achieved by reducing landmark illustrations (points of interest, POIs) to self-designed ones with clear textual labelling. Depending on the zoom level, the POI display was changed between (1) POI icon and POI text, (2) POI text or (3) POI icon.

The current position of the user was visualised with a white/black arrow icon (egocentric view). The position was determined by GPS using a route-matching algorithm to filter inaccuracies. For the first iteration, we decided to display a semi-transparent, blue-white directional arrow representing turn directions based on a 7-sector model (Klippel et al. 2004) whenever a user was in the range of a decision point. Participants of the first iteration evaluated the additional direction information as not necessary. Some participants claimed that the arrow faded in too late – due to sensor inaccuracies – which they considered confusing. For the second iteration, it was decided to remove the directional arrow. Finally, to keep test persons oriented, the user interface allowed – by pressing the button in the middle of the header – to zoom in and out for a better overview and readability of street names. By default, the map was displayed in zoom level 18 (maximum was zoom level 19).




(A) Legend for Figure (B) and Figure (C)

(B) Map interface of 1st iteration

(C) Map interface of 2nd test iteration

Figure 3. (A) Legend for Figure 3B and Figure 3C. (B) Map interface with route overview, egocentric view, distinction between past and future path, zooming and scrolling function, and turn direction arrow (implemented as custom map overlays). (C) Revised map interface of 2nd test iteration.

## 5. Results and discussion

This section presents and discusses results comparing the first and second iteration of the field study by means of pre-defined measures (see Section 3.4).

### 5.1 *Sense of direction*

Results of the SBSDS (first iteration: $M = 4.63$, $SD = 0.89$; second iteration: $M = 4.89$; $SD = 0.72$) revealed no significant differences between the 24 participants in each test iteration, which is an indication for a balanced group of participants. Moreover, no significant differences in both iterations between male and female participants as well as between participants of different age groups were found. As revealed in the previous studies, female participants estimated their sense-of-direction worse than male participants (first iteration: female: 4.36 (0.98), male: 4.91 (0.72); second iteration: female: 4.60 (0.67), male: 5.39 (0.55)). It is worth to notice that – following the previous work (Ishikawa et al. 2008) – we reversed positively stated questions to negatively stated ones so that higher scores mean a better sense of direction.

### 5.2 *Task completion time*

For both test iterations, participants were observed regarding their task completion time (with and without stops). As sub-routes were not equally long, task completion times varied between the routes. Figure 4 shows that, in general, actual walking time (without stops) for the second iteration was longer than for the first iteration (except of age class 1 where walking time decreased with the user interfaces voice and digital map).

As follows from Figure 5, average task completion time increased for the second iteration, too. Nevertheless, looking at the descriptive mean scores, the trend remains the same over both iterations: participants using AR technology needed the longest time for completing the navigation task on all three sub-routes. On sub-route 2, participants navigating with voice-only guidance were the fastest to complete the task with digital map users only slightly slower. On the first and third sub-route, however, digital map users were the fastest to complete the navigation task.

Furthermore, while on sub-route 1 there was no significant difference regarding task completion times, we found a significant increase on sub-route 2 ($F$ (1, 46) = 9.359, $p$ = 0.004). To explore this phenomenon, we did a correlation analysis between task

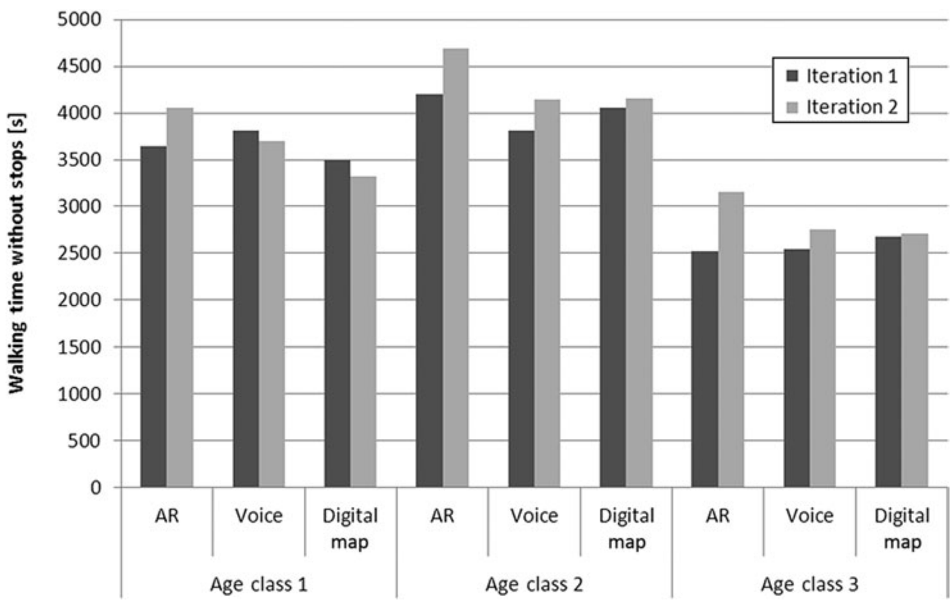



Figure 4. Walking time by technology and age class.

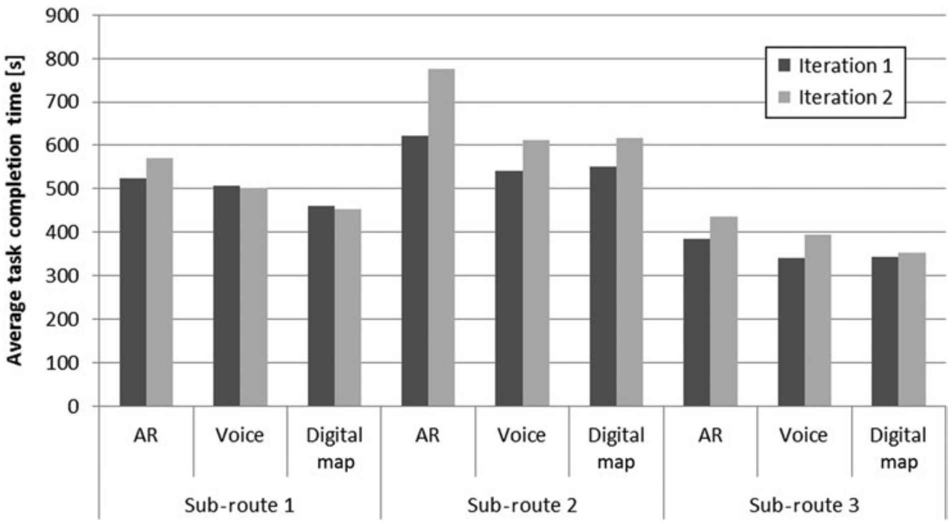



Figure 5. Task completion time by technology and sub-route.

completion time and duration of stops which showed a high correlation with high significance for the second iteration ($r = 0.96$, $p < 0.001$). The reasons and details for the increase in stops and therefore longer task completion times for the second iteration are discussed in the next section.

### 5.3 *Stops*

As can be concluded from Figures 6 and 7, participants stopped their walk more often and longer during the second test iteration. Especially on sub-route 2, a significant increase could be identified.

Figure 8 reveals that the main reason for this result was an increase in traffic volume, which hindered test persons to cross streets more efficiently. The growth in traffic volume was mainly caused by a blockaded underpass in the vicinity resulting in a redirection of traffic through the test area. Further reasons were red traffic lights, increased waiting times at

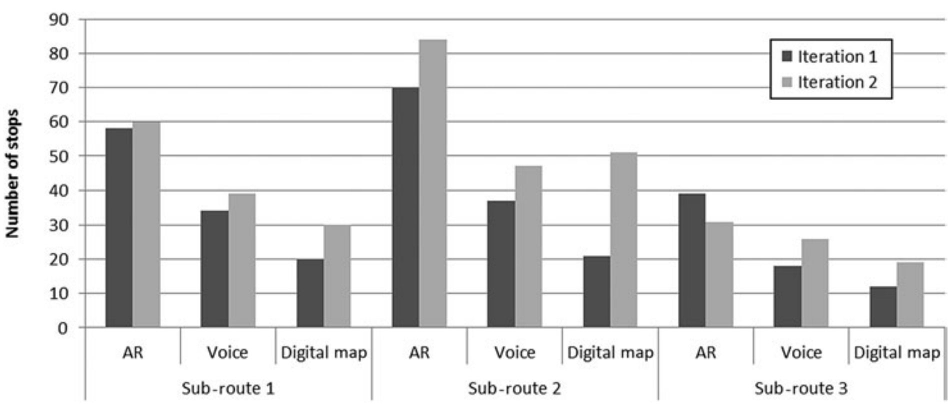



Figure 6. Number of stops by modality and sub-route.

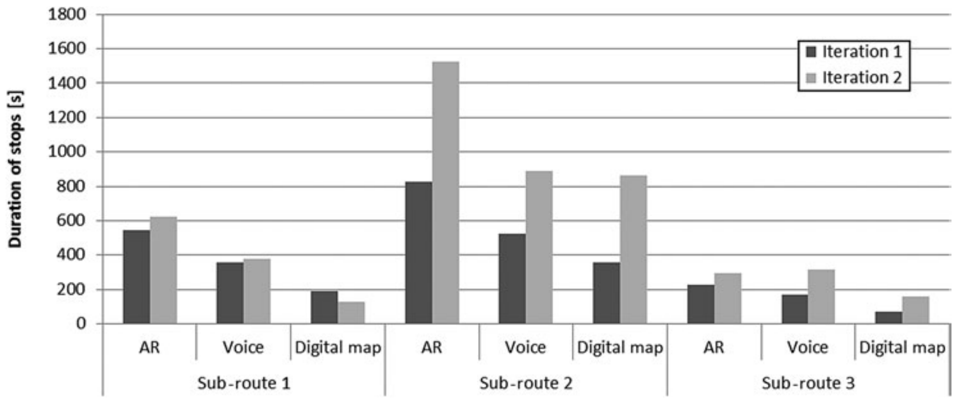



Figure 7. Duration of stops by modality and sub-route.

pedestrian crossings without traffic lights and crossing of streets without pedestrian crossings.

Another assessed aspect is the effect of inaccurate sensor signals (GPS, accelerometer, and magnetometer) for the different user interface technologies. As depicted in Figure 9, the most error-prone technology is AR: it requires accurate GPS positions as well as accurate values from magnetometer and tilt sensors in order to correctly overlay route information over the live camera view. Especially, the 3D view used during the second iteration required correct sensor signals; otherwise, the green bond extended into buildings or led to a wrong street/way regarding the next decision point. Therefore, effects such as GPS bouncing became particularly noticeable for participants and thus had negative effects on users' navigation performance. As a consequence, inaccurate signals caused a high number of stops because of uncertainty with respect to orientation (see also Figure 9). Nevertheless, sensor inaccuracies as well as orientation problems could be reduced from the first to the second iteration.

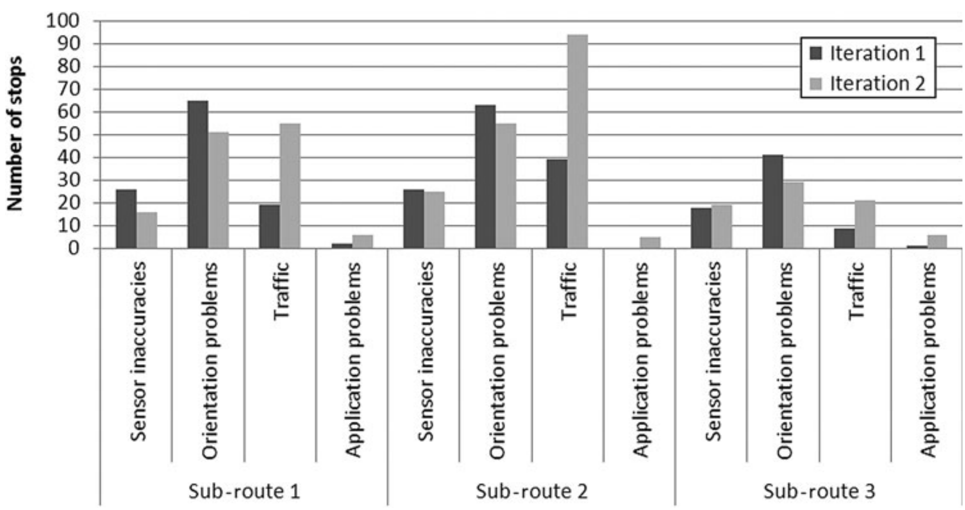



Figure 8. Number of stops by reasons and sub-route.

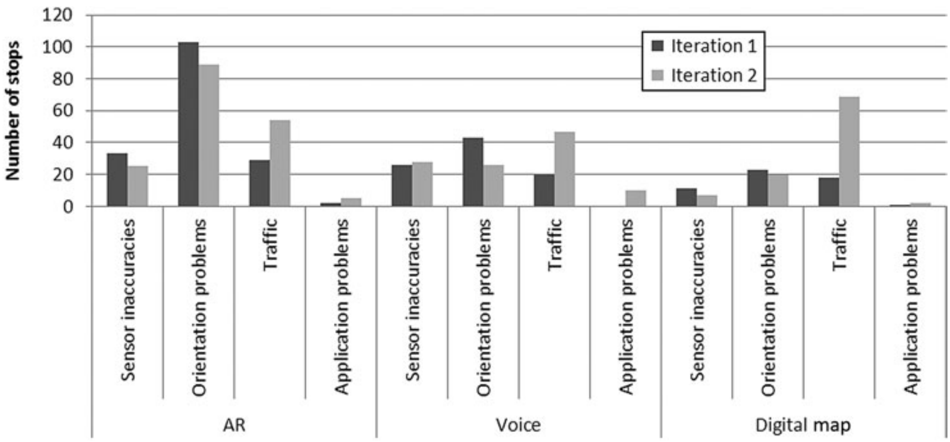



Figure 9. Number of stops by reasons and modality.

Moreover, results in Figure 9 reveal that noisy GPS signals do only have minor impact on navigation performance with a digital map. Reasons could be found in map matching algorithms filtering GPS noise. In contrast to AR and voice interfaces, the digital map interface does not work with timely instructions at decision points but with an overall route overview which is rather robust to positioning inaccuracies.

Results depict an increase in number of stops referring to application problems for the second iteration, particularly with voice-only guidance. Test records revealed that the main problem for participants was the loudness of the voice instructions. Although we used high quality earphones (but without noise-cancelling to ensure traffic noise awareness of participants, e.g. audible recognition of approaching or passing cars), some participants had problems to understand the commands because of increased ambient traffic noise. To find the right trade-off between ambient noise reduction and audible situation, awareness has to be considered as critical point of voice guidance during pedestrian navigation in inner city districts.

## 5.4 *NASA TLX*

The NASA TLX (Hart and Staveland 1988) is a subjective, multidimensional assessment tool that rates perceived workload on six different subscales: mental demand, physical demand, temporal demand, performance, effort and frustration. All test participants were asked to answer the questionnaire after successfully completing a sub-route in order to assess the effects of the different interface technologies on their cognitive load. As the RAW TLX version of the test was used, no weighing process of the different subscales was applied. Therefore, the individual task load scores for each person were computed by summing up the scores of each of the six scales and calculating the average score.

Results in Figure 10 show a significant increase in average task load concerning AR technology for the second iteration. The reason for this phenomenon can be found (again) on sub-route 2 which had the most complex decision points. Participants confirmed that they had more problems with orientation and needed longer time to re-orientate with the green bond interface (see Section 4.1) than with the 2D-approach of the first iteration.

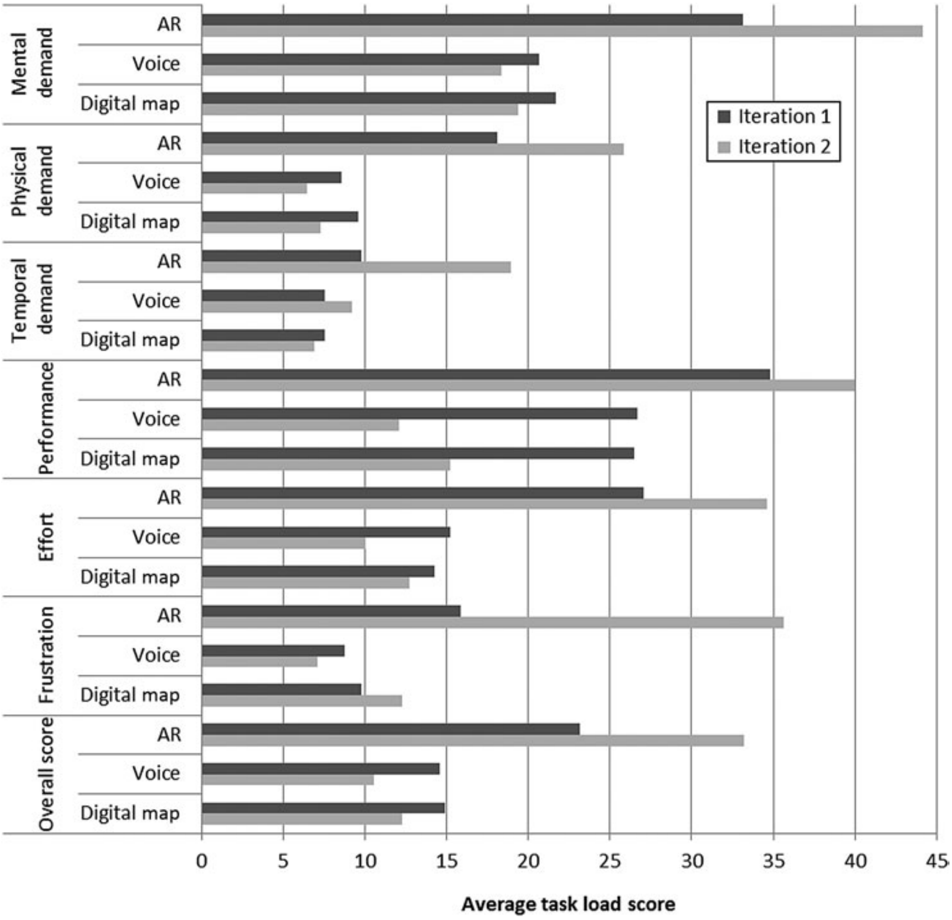



Figure 10. Results of NASA RTLX for each modality.

In contrast, digital map as well as voice-only guidance led to a lower task load score for both test iterations and could be further improved for the second iteration.

## 5.5 *System usability*

Figure 11 illustrates minor changes with regard to usability between the two iterations and a minor improvement with regard to digital map as well as voice-only interfaces.

For both iterations, AR was rated with lower usability scores than the modalities voice and digital map. This result was mainly influenced by sensor inaccuracies on sub-route 2 where AR navigation scored worse in all dimensions of the SUS. In addition, a multivariate ANOVA showed that the youngest age class (age class 1) rated AR significantly worse than the other two age classes. In contrast, we found a substantial improvement in usability concerning voice guidance when comparing results from the first and the second iteration ($F$ (1, 46) = 4.872, $p$ = 0.032). Results for AR and digital map did not significantly change between both iterations.

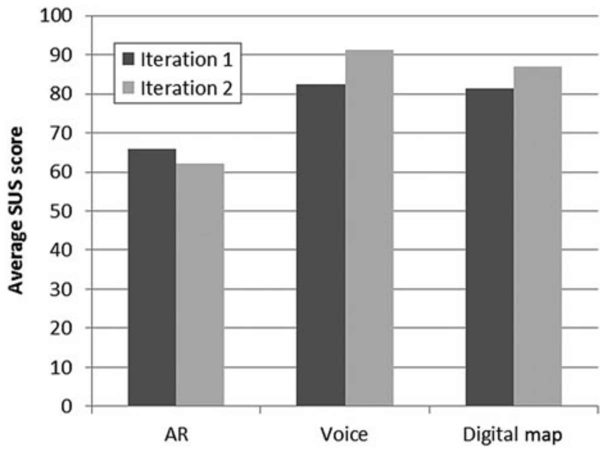



Figure 11. Results of SUS.

### 5.6 *Final questionnaire and age group analysis*

At the end of the experiment, each participant rated the tested system on a five-point Likert scale concerning (1) the efficiency allowing to fulfil the navigation task, (2) the fun factor of the application, (3) the cognitive workload, (4) the subjective feeling being on the right track and (5) the overall feeling of being guided. As follows from Figure 12, participants of both iterations rated AR significantly worse regarding the overall feeling of being guided by the application (first iteration: $\chi^2 = 16.333$, $p < 0.001$; second iteration $\chi^2 = 28.907$, $p < 0.000$). The other two navigation technologies did not reveal any significant differences between both iterations.

An analysis with respect to different age groups showed that in the second iteration participants from age group 1 (18–30 years) rated AR technology significantly worse than

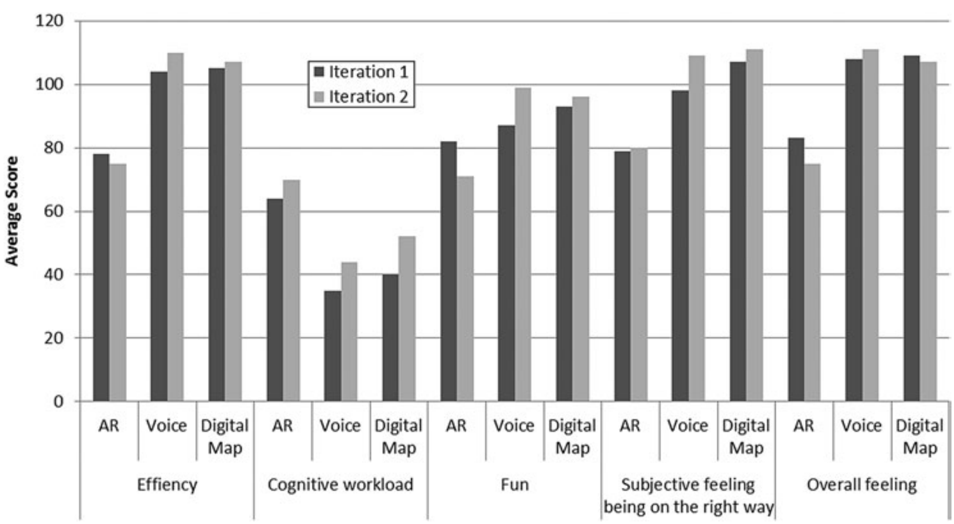



Figure 12. Results of final questionnaire.

for the first iteration. Results from age group 2 (31–60 years) show great similarities between both iterations. Participants from age group 3 (above 60 years) rated workload for digital map and voice-only guidance for the second iteration significantly better than for the first iteration.

## 6. Conclusions and outlook

To our knowledge, this is the first study comparing the three user interface modalities AR, voice and digital map for GPS-enhanced pedestrian navigation in the context of an *in situ* field study. One of the main goals was to study interaction and user experience with different navigation modalities in real-world settings while being aware of the differences to laboratory conditions. Interpretation of the results has to consider that real-world settings are prone to continuously changing conditions (e.g. distorted sensor signals, ambient noise or varying traffic situations) but lead to results reflecting particular challenges as well as shortcomings of modalities which may not be reflected under laboratory conditions. Thus, the study design is well-suited to reveal typical experiences of pedestrians navigating in inner city districts with commercially available high-end smartphones. Besides the real world setting, another unique aspect of the study was the separate testing of the three interface modalities by providing equal route information for all three interfaces. Furthermore, the study was concerned with an iterative approach conducting the experiment twice while considering feedback from the first iteration. The chosen methodology allowed us to intuitively understand user feedback from first iteration participants and consider the feedback for the second iteration. It is worth mentioning that the presented study followed a selective sampling approach by recruiting people of different age classes, with different navigation experience and personal/educational background to avoid bias in participants' selection. Furthermore, self-implementation of the smartphone interfaces has proven a useful decision as we could optimise interface modalities for the second iteration.

Concerning the challenge of equal environmental conditions for both iterations, we conclude that environmental causes such as increased traffic coming from re-routing can lead to significant effects on study results. As such factors may hardly be controlled, great importance should be placed on the recruiting of homogenous test persons/test groups in order to avoid further bias. Despite the disadvantages of higher effort and environmental uncertainties, study results show that experiments in real-world settings propose a great opportunity to observe users' behaviours and needs in everyday navigation situations and create high value for the development of future pedestrian navigation systems concerning both, user and technical requirements.

Concluding on results, navigation with AR view leads to significantly worse results regarding all assessed measures in comparison to voice and digital map interfaces. Participants needed longer to complete routes, more and longer stops have been observed and the imposed task load was rated significantly higher whereas the system usability was rated lower. When interpreting these outcomes, we have to consider that participants who, indeed, had practise with smartphones in general and in the context of pedestrian navigation were inexperienced with AR. Results indicate that participants felt uncomfortable while navigating with AR as they were not familiar with the technology. Especially, the handling of the smartphone during navigation revealed severe problems. For instance, some test persons continuously looked through the camera view of the device and had a high risk to stumble because of missed obstacles. We expected to reduce this phenomenon by changing the user interface from 2D to 3D design for the second iteration. Although we could achieve a slight decline in orientation problems, perceived workload of the test persons increased significantly during the second iteration (see results of NASA TLX). From these findings, we conclude that navigating with a 3D AR view demands more concentration from participants as they had to constantly follow the displayed path on the live picture of the camera (3D design), in contrast to navigating to the next target point (2D view). Furthermore, the 2D view is more resistant to GPS inaccuracies while the 3D view suffers from negative effects such as that the rendered path overlaps surrounding objects or points into buildings. Our field study clearly shows that sensor inaccuracies are hardly to overcome (e.g. insufficient turn information at road intersections) commercially available high end smartphones, which can be considered as major drawback of AR pedestrian navigation applications. It would be worth to set up further experiments focusing only on AR interfaces with alternative contents and styles as the current results indicate considerable influence of these aspects, e.g. as proposed by Mulloni and Schmalstieg (2012), to evaluate a less symbolic way of communicating navigational instructions. To overcome sensor inaccuracies, it could be worth to follow the path of image-based AR, which has been successfully applied to indoor environments but is not ready for being used for complex outdoor environments such as city centres. However, image-recognition on smartphones has the potential to overcome the problem of inaccurate sensor measurements and to significantly improve accuracy of AR displays (see also Walther-Franks and Malaka 2008). To summarise, although AR technology is ready to be used as interface for pedestrian navigation applications on smartphones, the technology is still suffering from usability and hardware problems leading to higher uncertainty of navigating persons.

From the experiment we conclude that people are used to electronic navigation assistance with digital map and voice-only interfaces, and thus study results reveal similar results regarding navigation performance and user experience. We could demonstrate that voice-only navigation with carefully composed voice instructions leads to similar results concerning navigation performance and user experience as navigation with digital maps, although voice-only interfaces have been rated worse by several authors of previous studies (e.g. Goodman, Brewster, and Gray 2005). Despite quantitative results, qualitative findings (SUS, NASA TLX and final questionnaire) showed that digital map and voice have a significant edge over AR regarding almost all aspects, too. Results also reveal that individual participants either prefer the one or the other technology, and most of the participants suggest a combination of both interface modalities. Thus, another open issue for further research would be to conduct a comparative evaluation investigating user experience and navigation performance of complementary interfaces, including the quantitative and qualitative measures of effectiveness, efficiency and satisfaction in different pedestrian navigation situations.

## Notes

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