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Applying user-centred design for smartwatch-based pedestrian navigation system

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ABSTRACT
The characteristics of a smartwatch impose several challenges regardig the design of a pedestrian navigation aid. This paper illustrates how landmark-based pedestrian navigation systems for smartwatches can be developed, considering the small screen sizes as well as the very limited interaction capacities of these wrist-worn devices. Particularly, by the use of a user-centred design approach, an initial user interface was developed, tested, and refined in two field experiments to create a final user interface. A combination of map view and direction view was proposed, where the map view provides an overview of the environment and route, while the direction view gives clear instructions (turning information) for decision points. The interface was further enhanced by the use of vibrations before decision points. In addition, landmarks were carefully considered and incorporated into both map view and direction view. The field experiments showed that these key features of the revised interface can effectively support pedestrian navigation via smartwatches.

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Pedestrian navigation; smartwatch; landmark; user-centred design; field study

1. Introduction

Electronic devices have become a major means for pedestrian navigation in the last decade, the most prominent one being the smartphone. In the last couple of years, smartwatches have risen in the public's attention. Smartwatches, such as Apple Watch and Android Wear OS watches, are wrist-worn electronic devices which are equipped with sensors and provide input/output capabilities. In the context of pedestrian navigation, smartwatches have important benefits over their smartphone equivalents (Wenig et al. 2015): Using smartphone in this context requires a user taking the phone out of the pocket and holding it in one's hands, while when navigating via smartwatches, the user can get navigation guidance right from their wrist without having their hand being occupied. In other words, smartwatches allow a hands-free use of navigation guidance, without disrupting the navigation task (Helgath, Provinsky, and Schaschek 2015).

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However, the limited screen sizes of smartwatches (typically 10 to 18 cm2, only a tenth to a quarter the size of a typical smartphone screen) impose challenges regarding the design of smartwatch-based pedestrian navigation systems. Research on this aspect is still on an early stage. D. Wenig et al. (2015; 2016) presented one of the several studies on this, and they transformed 2D route maps or images into a one-dimensional strip that can be scrolled on smartwatches to support indoor navigation. However, landmarks, which are considered as essential to supporting pedestrian navigation (Daniel and Denis 1998; Richter and Winter 2014), were still not integrated into these designs. This seems to be also the case of existing navigation systems for smartwatches, like Google Maps for Android Wear OS and Apple Maps for Apple watchOS, which simply present turn-by-turn instructions with street names. As an exception, N. Wenig et al. (2017) presented a first study on landmark-based navigation system for smartwatches, with a focus on enriching turn-by-turn verbal/written instructions with a single global landmark (e.g. tall buildings like TV tower, or mountains) while ignoring local landmarks that are essential for users to make correct turning decisions along the route. It is still unclear how local landmarks can be integrated into smartwatch-based pedestrian navigation systems, particularly map-based ones.

This paper proposes a landmark-based pedestrian navigation system for smartwatches, with a focus on the user interface design of local landmark-based route maps. We particularly consider the challenges brought by the small screen sizes and limited interaction capacities of these wrist-worn devices. Specifically, we illustrate how a user-centred design (UCD) approach can be applied in this context: An initial user interface was developed by considering the findings related to human wayfinding and navigation guidance in the literature. The interface was tested by participants in a field experiment to gather their opinions and feedback, which were then used to refine the initial interface, and produce a revised user interface. This new interface combined a map view and a direction view, where the map view provides an overview of the environment and route, while the direction view gives clear turning information for decision points. Landmarks and vibration before decision points were also incorporated into the interface. The interface was then evaluated again with participants in another field experiment to illustrate its usability, and identify potential improvements. As can be seen from the evaluation, the combination of map view and direction view together with the inclusion of landmarks in both views help to address the challenges brought by the small screen sizes and limited interaction capacities of smartwatches for smartwatch-based pedestrian navigation.

This paper proceeds in five additional sections. An overview of the relevant research is given in Section 2. Section 3 describes the methodology, i.e. applying the UCD process. We present the evaluation of the revised interface in Section 4, and discuss the evaluation results in Section 5. Section 6 concludes the paper, and points out further research directions.

2. Related work

2.1. Navigation, landmarks and mobile navigation systems

Montello (2005, 257) defines navigation as 'coordinated and goal-directed movement through the environment by organisms or intelligent machines'. It consists of wayfinding and locomotion. Wayfinding is the planning and decision-making part of navigation, and it determines a route between origin and destination, supported by a cognitive map of the environment or external artefacts such as maps. Locomotion (or route following) is the movement of one's body around an environment. During locomotion, people constantly monitor their local surroundings. Objects of the real world (local surroundings) are compared with memories stored internally or external artefacts such as maps or verbal route instructions for making turning decisions and confirmation ('am I still on the right track?'). This process continues until the destination is reached (Golledge 1999; Downs and Stea 1973; Gartner et al. 2011).

Mobile navigation systems are designed to assist peoples navigation tasks in unfamiliar environments. Three interacting components that define navigation should be addressed when developing mobile navigation systems (Huang and Gartner 2010), namely positioning (identification of users current location, e.g. using GPS, Wi-Fi or Bluetooth), path planning (computation of a suitable route from a start to a destination), and guidance along the path (communicating navigational/route information, e.g. turn information, via maps or verbal descriptions). This paper mainly focuses on the last one – route communication. Different communication forms have been employed for route communication, such as mobile maps (Rehrl et al. 2014), 3D (Lertlakkhanakul et al. 2009), verbal instructions (Fellner, Huang, and Gartner 2017; Bartie et al. 2018), haptic (Velzquez et al. 2018), and augmented reality (Rehrl et al. 2014). While smartphones are still the main mobile client for supporting navigation, recent research has also explored navigation on various wearable devices, such as smartwatches and digital glasses. Please refer to Section 2.2 for a review on smartwatch-based pedestrian navigation systems.

The term landmark stands for a salient object in the environment that aids the user in navigating and understanding the (Sorrows and Hirtle 1999). The importance of landmarks for navigation has extensively been discussed in the literature (Daniel and Denis 1998; Richter and Winter 2014). Undisputedly, landmarks are essential elements in navigation systems. Different methods have been developed to provide landmark-based route instructions (Raubal and Winter 2002; Duckham, Winter, and Robinson 2010; Fellner, Huang, and Gartner 2017), and landmark-based route maps (Li et al. 2014; Elias and Paelke 2008). In these studies, the inclusion of landmarks in navigation systems has been shown to be beneficial, not only for improving navigation performance, but also for supporting incidental spatial knowledge acquisition during navigation.

2.2. Smartwatches and navigation systems

Smartwatches are wrist-worn electronic devices that are nowadays usually paired with a smartphone. Compared to smartphones which users need to hold in their hands, smartwatches potentially allow a more natural way of mobile human-computer interaction, as the user can get information by simply turning their wrist. However, their limited screen sizes pose significant challenges in designing smartwatch-based mobile applications (Rawassizadeh, Price, and Petre 2014; Wenig et al. 2015). Very often, the smartwatch acts as an additional interface to a paired smartphone, which forwards notifications to be displayed on the smartwatch (Schirra and Bentley 2015). To address the issue of small screen sizes as well as the related 'fat finger problem' (Siek, Rogers, and Connelly 2005), many studies regarding smartwatch interactions explore additional input techniques (Oakley and Lee 2014; Xiao, Laput, and Harrison 2014).

Despite the small screen sizes and limited interaction capacities, recent years have seen an increasing interest in using smartwatches to support pedestrian navigation. In early research, smartwatch was often used as an extension to smartphones, e.g. SubwayPS (Stockx, Hecht, and Schoening 2014). Recent research started to place the smartwatch itself into the centre. Several studies developed vibrotactile-based navigation guidance on smartwatches (Dobbelstein, Henzler, and Rukzio 2016; Cugnet et al. 2017). There are also studies focusing on visual-related guidance on smartwatches, addressing the challenges of small screen sizes. D. Wenig et al. (2015) introduced StripeMaps to support indoor navigation, which transforms 2D route maps into a one-dimensional strip that can be scrolled on smartwatches. The same concept has been applied for designing image-based indoor navigation systems (Wenig et al. 2016). However, landmarks, which are considered as essential to supporting pedestrian navigation, were still not integrated into these designs. This seems to be also the case of existing navigation systems for smartwatches, like Google Maps for Android Wear OS and Apple Maps for Apple watchOS, which simply present turn-by-turn instructions. They mainly rely on simple arrows showing the next turning direction, combined with the name of the street on which the user has to turn. Helgath, Provinsky, and Schaschek (2015) employ smartwatches and speech recognition to collect data about landmarks. However, they did not investigate the use of landmarks in smartwatch-based pedestrian navigation. To the best of our knowledge, N. Wenig et al. (2017) present the first study on landmark-based navigation system for smartwatches. They mainly focus on enriching turn-by-turn verbal/written instructions with a single global landmark (e.g. tall buildings like TV tower, or mountains). They ignore local landmarks that are essential for users to make correct turning decisions along the route. To summarize, there exists a gap on how local landmarks can be integrated into smartwatch-based pedestrian navigation systems, particularly map-based ones, considering the small screen sizes and limited interaction capacities of these wrist-worn devices.

2.3. User-centred design

User-centred design (UCD) can be defined as a flexible, multi-stage, and iterative process during which an interactive system (e.g. a map-based application) is continuously evaluated by its intended users to gather their opinions and feedback, prompting subsequent refinement to its deficient aspects (Nielsen 1994; Roth, Ross, and MacEachren 2015). The key principle is to involve users already at the design phase. UCD has been increasingly recommended for interactive maps and cartographic products (Haklay and Nivala 2010; Tsou 2011; Roth et al. 2017), and has been applied for the design and evaluation of various applications, such as geovisual analytics tools (Roth, Ross, and MacEachren 2015), geoportal (Gkonos, Iosifescu Enescu, and Hurni 2018), and smartphone-based pedestrian navigation systems (Rehrl et al. 2014). In these studies, UCD has been shown to be an effective method to ensure the systems being developed meeting users expectations.

3. Methodology: user-centred design

This paper aims to investigate how landmark-based pedestrian navigation systems can be developed for smartwatches, considering their small screen sizes and limited interaction capacities. The methodology of this work follows a user-centred design approach (Haklay and Nivala 2010; Roth, Ross, and MacEachren 2015). Specifically, the following steps are applied:

(1) *Design of an initial user interface* (Section 3.1): By analysing literature on human navigation, navigation systems, and smartwatches, we identify the important aspects to be considered when developing smartwatch-based pedestrian navigation systems, propose and implement an initial user interface.
(2) *Evaluation of the initial interface with users* (Section 3.2): We then evaluate the initial interface with users in a field experiment to collect what they like/dislike, and their experiences of using the prototype.
(3) *Refinement of the initial user interface* (Section 3.3): Feedback and opinions of the first field experiment are then analysed, and subsequently used to refine the design of the initial interface. Based on this, a revised user interface is proposed, and a corresponding prototype is implemented.
(4) *Evaluation of the revised interface with users* (Section 4): The second prototype is then evaluated in another field experiment to illustrate its usability, and identify potential improvements for further development.

3.1. Design of an initial user interface

Efficient navigation services should provide information which is tailored to the information needs of users during navigation (Gartner et al. 2011). Research on cognitive mapping and navigation has shown that routes are often conceptualized as a sequence of turns (Golledge 1999; Tversky 1992), and emphasizes the importance of clearly communicating turning directions at each decision point (Daniel and Denis 1998), e.g. with the help of landmarks (Tversky and Lee 1998; Richter and Winter 2014). Further literature (Gartner and Radoczky 2005; Rehrl et al. 2014) provides some useful hints for route map design, such as 1) automatic adaptation of the presented map section to the position of the user, 2) the route should be visible to the user at all time, 3) the distinction between the past and the future path should be unambiguous, 4) decision point information should be conveyed in a clear and easy-to-understand manner, 5) landmarks should be included where possible to denote the position of decision points (e.g. 'choice point' landmarks in Lovelace, Hegarty, and Montello (1999)), and to keep users' confidence during route following (e.g.'on route' landmarks in Lovelace, Hegarty, and Montello (1999)).[1]

Based on the above literature, an initial interface design of the smartwatch-based navigation system was proposed (Figure 1). The interface can be described as a combination of a map view and a direction view, which is further enhanced by the use of landmarks and vibrations. The map view contains the map itself, and a red marker indicating the current location. The route is visualized as a coloured line, with the past path as a dashed line. The direction view mainly consists of an arrow representing the next turn the user has to take. The arrow uses an 8-sector model, where 7 directions can be used for providing route directions, while the eighth is used as the reference direction, as proposed by Klippel (2003). The

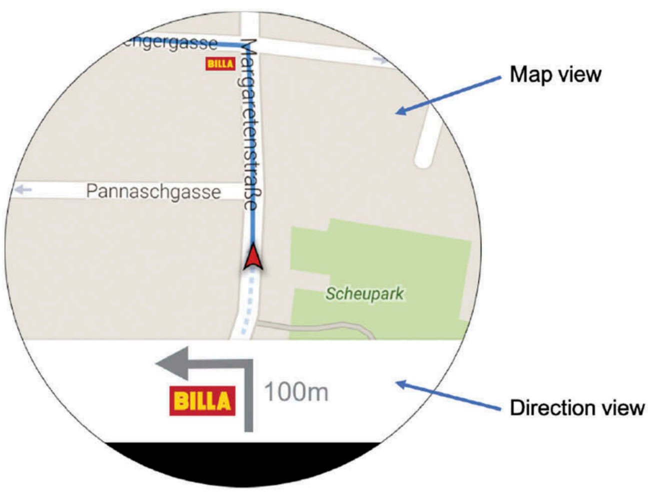


Figure 1. The initial user interface, featuring a combination of map view and direction view, and inclusion of landmarks.

direction view is located at the bottom on the screen and takes about 20–32% of the available screen height, depending on the visualization and amount of information shown. The combination of a map view and direction view on the one hand ensures an overview of the surrounding environment, on the other hand provides information of the turning directions and decision points in a clear and easy-to-understand way.

If appropriate, both map view and direction view also show a landmark to provide more information on decision points. Following the findings of Bauer, Müller, and Ludwig (2016), we restrict the number of landmark at a decision point to one. The visualization of landmarks is based on the suggestions of Elias and Paelke (2008), using either images, drawings, sketches, icon, symbols or words. The same visualization of a landmark is used in the map view and the direction view so that the user is able to match them against each other, though the landmarks in the direction view are bigger in order to make them more identifiable. In the direction view, the landmark is placed properly to reflect its relative position to the turning direction. Distance to the next decision point is also provided in the direction view.

In order to notify users that they have to perform a turning action, a one-second-long vibration is triggered when the user gets into the range of 40 m of a decision point. The vibrations are intended to lessen the burden of the users to check their smartwatches if they are still on the correct route as well as decrease the possibility of missing decision points. To avoid confusion and memory burden, the idea of using different vibration patterns to indicate left or right turns is discarded.

3.2. First field experiment: design and results

In order to gather feedback and identify problems of the initial user interface, a 'Wizard of Oz' experiment in the field was conducted. Furthermore, while research suggests that a track-up orientation of the map view is better perceived by users for navigation purposes (Radoczky 2007), the goal of the experiment was also to see whether track-up orientation is still preferred considering the small screen sizes of smartwatches. With track-up orientation, the map is always rotated in a way so that the following path segment is aligned to the top of the screen. In contrast, in the north-up map view, north is always located at the top of the screen.

3.2.1. Routes

Two routes (Route 1 and Route 2) in the fifth district of Vienna city (Austria) were chosen for the experiment, where the end of Route 1 is the start of Route 2 (Figure 2). Both routes are about the same length of 1 km. Route 1 has five turns while Route 2 has six.

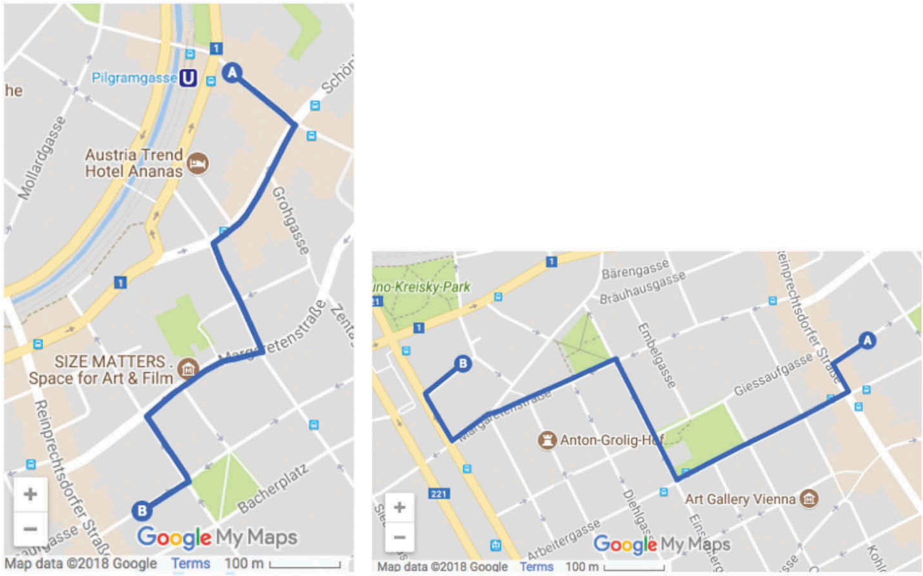


Figure 2. Routes of the first field experiment: Route 1 (left) and Route 2 (right).

3.2.2. Participants

Six participants, three females and three males, participated in the field experiment. Their ages ranged from 24 to 33. They were all unfamiliar with the test routes, and did not get paid for their participation.

3.2.3. Prototypes

Two mock-up prototypes, one with track-up map view and the other with north-up map view, were implemented for smartwatches, following the initial design described above. Landmarks were carefully selected from the environment by the authors manually, mainly considering their visual and structural salience (Sorrows and Hirtle 1999) and the findings of Elias and Paelke (2008). Both routes have turns with landmarks close-by and one turn each without a landmark. The prototypes were installed in a Motorola Moto 360 smartwatch.

3.2.4. Experiment design and procedure

Participants were randomly divided into two groups. A within-subject design and a counter-balancing consideration were used for the experiment: i.e. for Route 1, the two groups each used one of the mock-up prototypes. When they reached the end of Route 1, which is also the start of Route 2, they switched to the other prototype. The experiment consisted of an initial interview with a focus on the current knowledge and usage of navigation systems (in general as well as in regard to smartwatches), a field test, and a post-test interview with questions about the performed navigation task. During the field test, each participant had to navigate along the two routes while wearing the smartwatch which was connected to the smartphone of the researcher. The smartwatch showed the navigation interface as described above. In order to mimic the location updates, the interfaces were changed manually by the researcher via the smartphone at predefined locations. During the navigation task, the participant received no hints and the researcher walked several meters behind him/her. If he/she took a wrong turn or missed a turn, he/she was informed. Between Route 1 and Route 2, each participant had a short break of about 3 min. After they reached the end of Route 2, they were asked questions about the performed navigation task, particularly on the following aspects: problems during navigation, what they liked or disliked, how the navigation prototypes were used, which of the prototypes (north-up vs track-up) they preferred, how the combination of map and direction views was perceived, whether landmarks were beneficial, and potential improvements of the design.

3.2.5. Results

The field experiment was finished in April 2016. All participants successfully completed the navigation tasks. In general, the feedback regarding the initial user interface was very positive, while some potential improvements were also suggested. In the following, we describe and discuss the findings with respect to the key aspects of the initial interface.

(1) *Combination of map view and direction view*: Overall this feature was perceived as very useful by all participants, though the way how participants used the prototypes varied a lot. Whereas one participant reported that he mainly used the map view during navigation, all other 5 participants mentioned that they relied heavily on the direction view regardless which of the two prototypes was used.
(2) *Orientation of the map views*: Five out of 6 participants preferred the track-up orientation due to the reduced mental workload. However, the other participant did not particularly care, as he just used the direction view.
(3) *Landmarks*: The addition of landmarks to the map view and direction view were found by all participants to be beneficial because landmarks can be discovered from farther away than street names. Five of the participants mentioned that landmarks should only be shown when the actual object can be seen in the environment at the same time.
(4) *Vibrations*: The vibrations before decision points were perceived as very useful by all participants. One participant in particular merely checked the smartwatch but just waited for the vibrations and then checked the direction view for the next turn information.
(5) *Overview and interaction (suggestions for improvement)*: All participants mentioned that an overview of the whole route would be a necessity for

them, though some further mentioned that it might be sufficient to have an overview on the smartphone which can be checked when planning the route and then use the smartwatch from there on. Some participants also said that they would like to be able to scroll and zoom, mostly because they are accustomed to that feature from their smartphones. One participant mentioned that while she expected to be able to scroll, it appeared not to be necessary for the navigation itself.

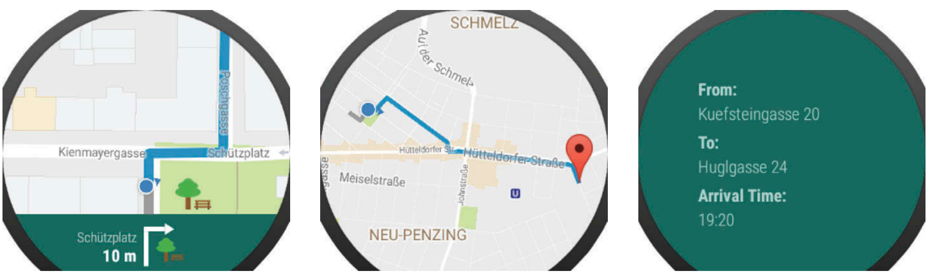
(6) *First path segment (suggestions for improvement)*: The first path segment of each route represented the greatest struggle for four of the participants, since they had to take their time to find out in which direction they have to start. Some participants mentioned that some kind of compass which indicates their bearing would be helpful.

3.3. Second interface design

Based on the findings and suggestions of the above field experiment, we refined the initial user interface. Basically, those features perceived as useful were kept, i.e. the combination of map view and direction view, track-up orientation of the map view, inclusion of landmarks in both map view and direction view, and vibrations before decision points. Following the suggestions by the participants, three new features were added:

(1) *Overview information of the route*: Now the new navigation application consists of three pages (Figure 3), which can be changed by the user via swiping with fingers. The first page ('turn-by-turn page') represents the main screen and consists of the map view and direction view. The second page ('overview page') shows an overview of the whole route, while the third page ("information page") provides additional information consisting of the addresses of start and end locations and an estimated arrival time.

(2) *Real-time bearing/heading*: We visualize the real-time bearing of the smartwatch as a blue arrow close to the 'you-are-here' icon (see the



(a) Turn-by-turn page. (b) Overview page. (c) Information page.

Figure 3. Overview of the user interface of the second design. Users can use their fingers to swipe and switch these pages.

small blue arrows in the map views in Figures 3 and 4), obtained from the magnetic field sensor as well as the accelerometer of the smartwatch. The visualized bearing allows the user to relate his or her direction to the orientation of the path, which helps with orientation, especially when starting to navigation (see 'first path segment' above) or on complex intersections.

(3) *Differentiation of non-subsequent and subsequent turns in the direction view* (Figure 4): In order to ease the decision of a user if a turn has to be made, subsequent and non-subsequent turns are distinguished. If the next street intersection on the way is not a turn in the designated path (i.e. users need to continue without turning left or right), the arrow in the direction view is dotted. If users need to make a turn at the next street intersection, the arrow is visualized as a solid line.

We discarded participants suggestions regarding adding scroll and zoom functions, as they seem to not be required for the purpose of navigation, and adding them would have introduced new problematic issues due to the limited screen sizes and 'fat-finger' problem. Furthermore, the introduction of an additional overview might already constitute a sufficient replacement for a zoom functionality. Thus, while an overview was added, scrolling and zooming were not considered in the second interface design.

4. Evaluation

In order to evaluate the revised user interface, a second field experiment was implemented. In the following, we describe the experiment design, and present the results.

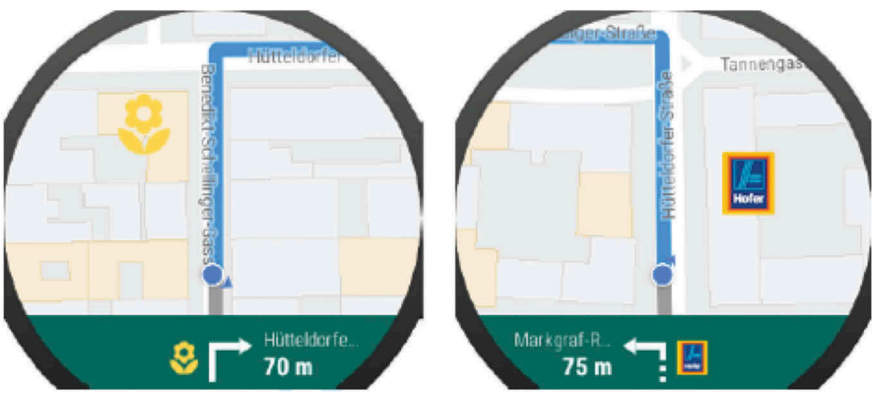


Figure 4. Differentiation of non-subsequent and subsequent turns in the direction view: solid line for subsequent turns (left), and dotted line for non-subsequent turns (close to the bottom of the screen), i.e. street intersection without turning action needed (right).

4.1. Experiment design

Again, two different routes (Route 1 and Route 2) in Vienna were carefully selected (Figure 5), considering the route distance, number of turns, and intersection complexity. The end of Route 1 was the start of Route 2. They are 1154 and 1076 m long each and have six turns.

4.1.1. Participants

Sixteen participants, eight females and eight males, participated in the field experiment. The mean age was about 28 years (range 24–33). They were not paid for their participation. All participants were unfamiliar with the routes.

4.1.2. Prototypes

The revised interface design was implemented for the two routes to create a navigation prototype for smartwatches. The prototype obtained real-time location via GPS on its paired smartphone, and bearing information from the magnet field sensor as well as the accelerometer of the smartwatch. For the map view, we used Google Maps as the base map. However, it is important to note any base map can be used. Landmarks were carefully selected for the two routes, where Route 1 includes a park, a bank and a grocery store, while Route 2 has a bakery, a florist, and a grocery store. They were visualized as symbols or logos as suggested by Elias and Paelke (2008), in both map view and direction view. Figure 6 provides some screenshots of the prototype, highlighting how landmarks were visualized for both routes. To evaluate the benefits of including landmarks, another prototype was created, which replaced landmarks with street names.[2] Figure 7 provides a screenshot of the street name-based prototype, corresponding to the 'turn-by-turn' page in the landmark-based prototype shown in Figure 3 (a). In the following, we refer these two prototypes as landmark-based prototype, and street name-based prototype. Both prototypes were installed in a Motorola Moto 360 smartwatch.

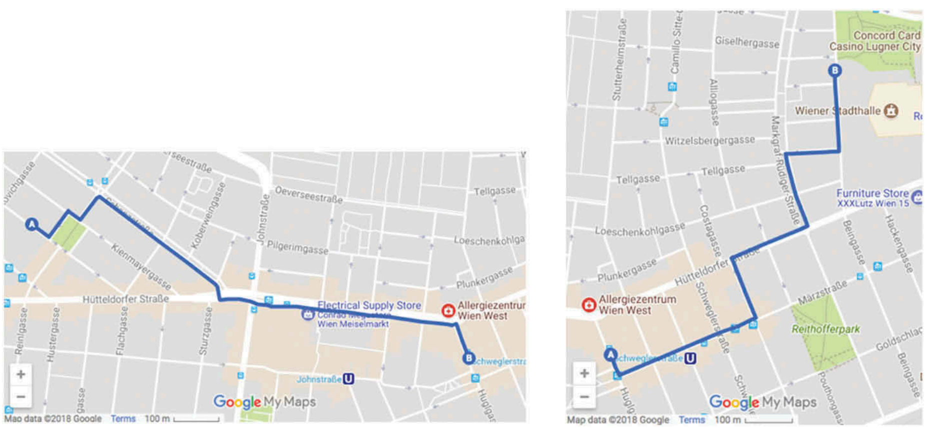
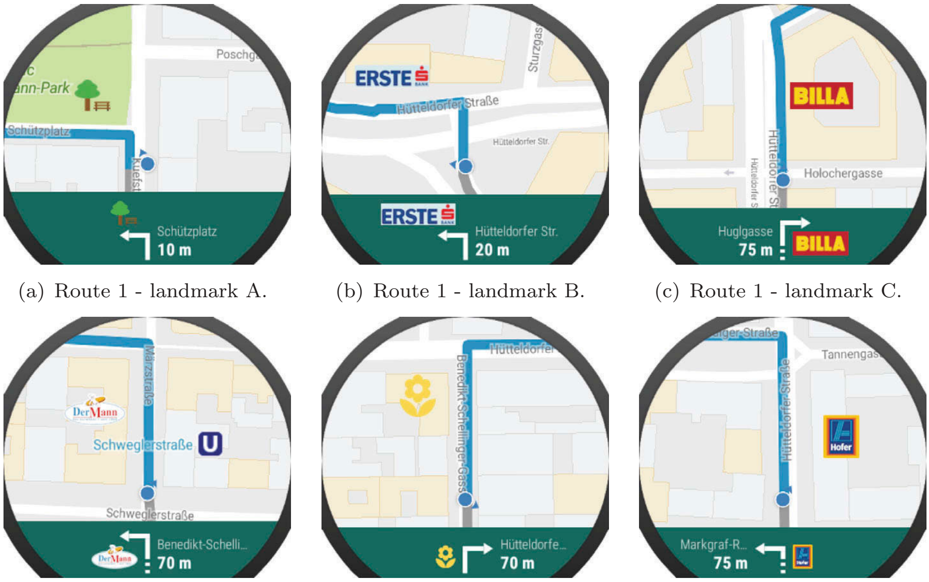


Figure 5. Routes of the second field experiment: Route 1 (left) and Route 2 (right).



(a) Route 1 - landmark A. (b) Route 1 - landmark B. (c) Route 1 - landmark C.

(d) Route 2 - landmark D. (e) Route 2 - landmark E. (f) Route 2 - landmark F.

Figure 6. Screenshots of the landmark-based prototype, showing how landmarks were visualized for both routes.

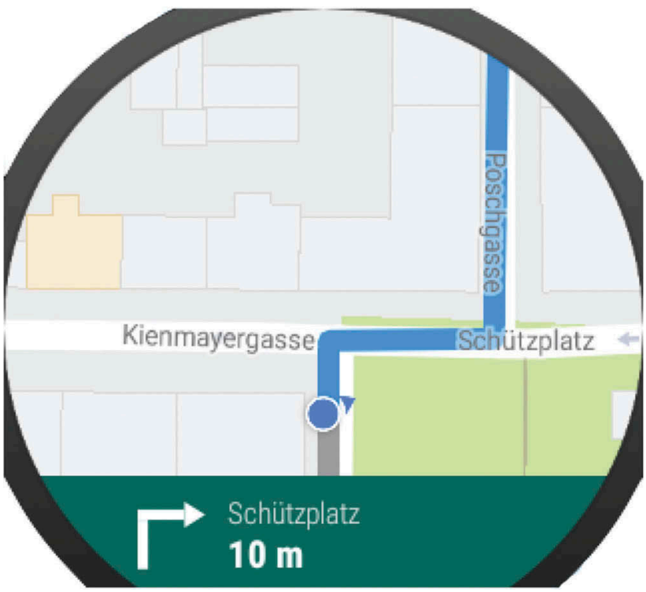


Figure 7. A screenshot of the street name-based prototype, corresponding to the 'turn-by-turn' page in the landmark-based prototype shown in Figure 3 (a).

4.1.3. Experiment design and procedure

Participants were randomly divided into two groups, each with eight participants (four females and four males). A within-subject design and a counterbalancing consideration were used for the test, i.e. for Route 1, the two groups each used one of the navigation prototypes. When they reached the end of Route 1, which is also the start of Route 2, they switched to the other prototype. Each participant was accompanied by one researcher, who observed the test run and guided through the interviews. Participants' interaction with the navigation prototypes and task completion time were logged on the smartwatch.

At the beginning, the participant had to complete the Santa Barbara Sense of Direction Scale (SBSOD) test (Hegarty et al. 2002) to assess his/her spatial abilities. Afterwards, the participant was given a short description of the field experiment. The smartwatch was given to the participant, and the navigation prototypes were briefly demonstrated.

After a brief training session, the participant was led to the start of Route 1 and instructed to follow the designated route and to reach the destination given by the prototype. During the navigation task, no hints were given or questions answered. The researcher walked several meters behind the participant in order to avoid any influence or bias. When the participants reached the destination of Route 1, they had a short break, and the prototype on the smartwatch was switched. Afterwards, the user was asked again to follow the designated route until the destination.

After the navigation task, the participant had to complete the NASA-TLX (Hart and Staveland 1988) for each route, which assesses their perceived workload. Furthermore, a semi-structured interview was conducted to gather feedback about the prototypes and their usages.

The same procedure was applied to each participant. Each test was completed within 1 h in total.

4.2. Results and discussion

The field experiment was completed in April 2017. All participants successfully completed the navigation tasks. This section presents and discusses the main results of the field experiment.

4.2.1. Sense-of-direction (SBSOD)

For each participant, we calculated the mean value of his/her answers to the 15 questions of the SBSOD. Similar to Rehrl, Husler, and Leitinger (2010), we reversed negatively stated questions to positively stated ones so that a higher score means a better sense-of-direction. The results of the SBSOD (mean value = 4.19, SD = 1.00) revealed no big difference in sense-of-direction between the 16 participants. Female participants estimated their sense-of-direction worse than males (Female: 3.88 (1.02), Male: 4.5 (0.95)). Since the calculated mean value in Rehrl, Husler, and Leitinger (2010) is similar (mean = 3.89; SD = 0.76), we consider our test group as balanced regarding sense-of-direction.

4.2.2. Task completion time

For the navigation task, participants were observed regarding their task completion time. Figure 8 shows that no clear pattern is observed regarding this aspect. For Route 1, using the landmark-based prototype leads to a longer task completion time, compared to using the street name-based prototype (832 vs. 779 s). However, for Route 2, using the landmark-based prototype leads to a shorter task completion time (770 vs. 842 s). Due to the distribution of the data, a non-parametric Wilcoxon signed-ranked test (two-tailed paired) was performed to assess these differences. Results of the test showed no significant difference for Route 1 ($Z = -1.01$, $p = 0.31$), but significant difference for Route 2 ($Z = -2.66$, $p = 0.008$).[3]

4.2.3. Screen-on of the smartwatch

During the field experiment, we also captured when and where the screen of the smartwatch went on or off. The gathered data can be used to get a sense about how often participants needed to use the navigation system to get route instructions. Surprisingly, in terms of screen-on duration, using the landmark-based prototype or the street name-based prototype leads to similar results: landmark-based (mean = 120.25 s, SD = 101.82 s), and street name-based (mean = 120.56 s, SD = 114.33 s). A non-parametric Wilcoxon signed-ranked test (two-tailed paired) showed the difference was not significant ($Z = -0.52$, $p = 0.61$).

Figure 9 shows the locations where the smartwatch screen goes on when using the landmark-based prototype. Heat maps for both routes are presented where a darker shade of red indicates that more participants had their smartwatch active at that particular location. As can be seen, participants used their smartwatch

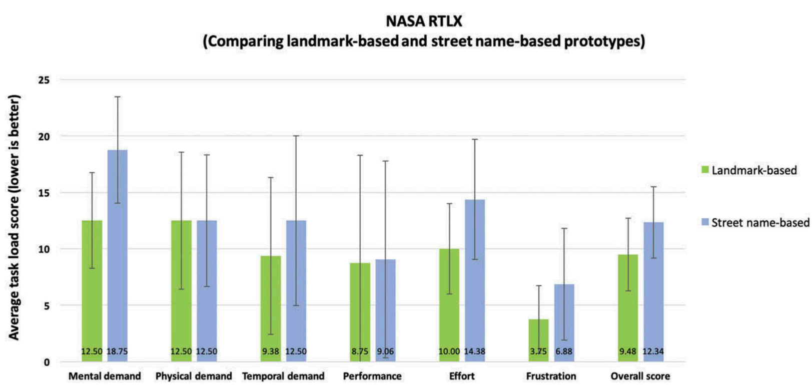
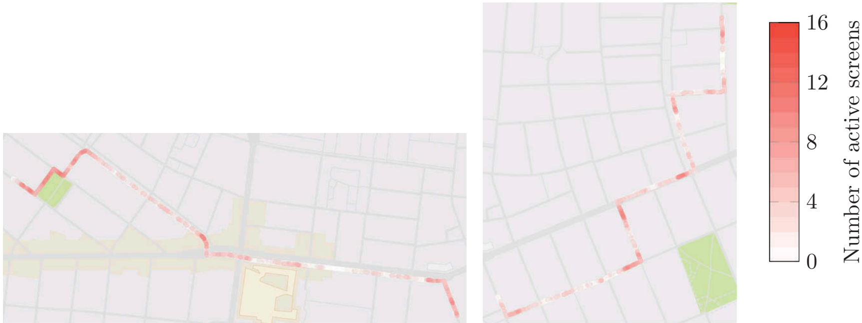


Figure 8. Results of the task completion time. Vertical error bars denote 95% confidence intervals.



(a) Route 1 (b) Route 2

Figure 9. Heat maps of the locations where the smartwatch screen was on when using the landmark-based prototype. A darker shade indicates that more participants had their smartwatch turned on at the particular location.

heavily at decision points. This seems natural since the smartwatch vibrates and participants check it for information about the decision point. On the other hand, along with longer path segments participants used the smartwatch to reassure themselves. It should be noted that while not visible in Figure 9 the heat maps of the two prototypes do not differ.

4.2.4. Decision errors

When participants made an error during the navigation the event was noted by the researcher. Two participants made an error where they walked straight for a few meters after a decision point instead of taking the turn. One occurred when using the landmark-based prototype, and the other with the street name-based one. It should be noted that in the case of the landmark-based prototype there was no chosen landmark at that particular decision point which might have made an impact. For both cases, the errors were corrected by the participants themselves without intrusion from the researcher. Both participants mentioned that they did not take the turn because the marked location on the map had been behind their actual location and thus they thought they were not yet there. It should furthermore be noted that if the cause of the errors was indeed the GPS, then the vibrations at the decision points did not trigger since the prototypes were not aware that the user was already close enough.

4.2.5. Perceived workload: NASA RTLX

In order to assess the perceived workload (cognitive load) of participants during the navigation tasks, a NASA TLX was conducted for each route, which assess six different subscales: mental demand, physical demand, temporal demand, performance, effort and frustration. We used the RAW TLX version of the test (NASA RTLX), i.e. no weighting process of the different subscales was applied. Therefore, the individual overall scores for each participant were computed by averaging the scores of each of the six scales.

Figure 10 shows the mean values for all six subscales and the overall scores for each navigation prototype. On average, participants felt that the landmark-based prototype performed better than or equal to the street name-based version on each subscale. Wilcoxon signed-ranked tests (two-tailed paired) showed that the differences were significant for the subscales 'mental demand' ($Z = -2.39$, $p = 0.017$) and 'effort' ($Z = -2.32$, $p = 0.021$). When combining all subscales together, a task load index of 9.48 for the landmark-based prototype, and a task load index of 12.34 for the street name-based prototype can be calculated. A non-parametric Wilcoxon signed-ranked test (two-tailed paired) showed the difference was significant ($Z = -2.38$, $p = 0.018$). This indicates that the perceived workload is significantly lower with the landmark-based prototype than with the street name-based one.

4.2.6. Interviews

In order to gather detailed feedback, semi-instructed interviews were conducted after participants reaching the end of Route 2. In the following, we summarize the results.

Overall the general impression of participants regarding both prototypes was very positive. Participant L, for example, remarked: 'I did expect it to be much more complicated, because of the small display I did not anticipate that it would be so easy'. Participants reported that they mainly used the turn-by-turn screen and rarely switched to the overview screen or the information screen. One common negative remark from some participants was that the shown location on the smartwatch was not as accurate as it could have been.

Participants described the user interface (i.e. combination of track-up map view and direction view) as self-explanatory and easy to understand. This was also observed during the navigation tasks since participants grasped the handling of the applications very fast and did not require any kind of help. Participant K especially mentioned: 'I didn't have the feeling that I had any problems or

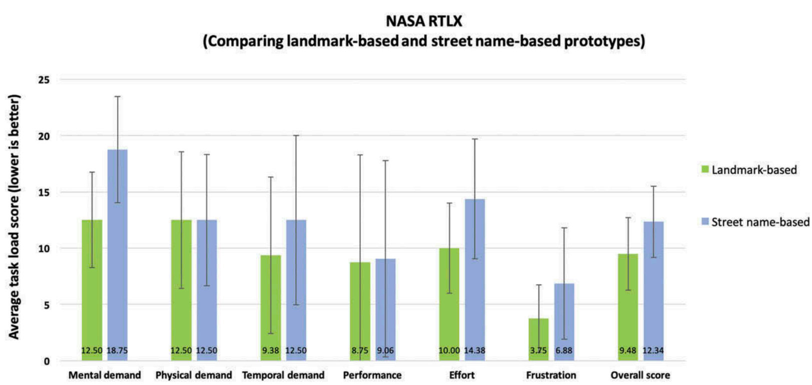


Figure 10. Mean values of NASA-RTLX subscales for the landmark-based prototype and street name-based prototype. Vertical error bars represent the 95% confidence intervals.

complications since interaction was hardly required, which I find positive because while I'm on the way and while I'm walking I don't want to be forced to interact and don't want to align the map myself'.

The vibrations before decision points were positively perceived by all participants. Participants overall felt that they could rely on this form of feedback and thus did not need to check their smartwatches often, as for example participant F mentioned: 'I only paid attention to the vibration, then took a look onto it and checked where I had to go'.

The bearing indicator, which shows the heading of the user, was not used by all participants. The participants who did only used it at the start of the routes in order to orientate themselves. Once participants had oriented themselves the automatic rotation (i.e. track-up) of the map in combination with the arrows in the direction view were sufficient for any further wayfinding. However, some participants found that the bearing indicator was not very precise and lagged behind their rotation movement.

When comparing the landmark-based and street name-based prototypes, all participants preferred the landmark-based one. All participants found the landmarks to be more beneficial and easier to use than street names, as for example participant K mentioned: 'The first version with the landmarks was much better, because at least for me the landmarks helped a lot in not having to look at the display but just needing to know for what I had to look for and also don't watch for street names'. Participant M felt that landmarks are more natural than street names, and are also often used when describing routes to other people. The use of landmarks increased the confidence of participants that they are on the correct path and added a reliable reference point.

When asked if they preferred the used prototypes from the field experiment over their usual navigation aid via smartphone, most participants found that the smartwatch provided crucial benefits when it comes to navigation. Since the smartwatch could be worn on the wrist, users did not have to take it out of their pocket to check for information, as for example participant J mentioned: 'The handling of the smartphone is more cumbersome. I have to take it out of the pocket, need to turn the display on, enter my unlock code and then I have the map open. This is an advantage of the smartwatch since there I raise my arm and tap the display and the thing I want to see is immediately active'. Furthermore, participants felt that the vibrations on the wrist could not be missed which increased the assurance that they are on the correct path. One downside participants mentioned was that the screen size of the smartwatch is naturally smaller when compared to the smartphone and thus provides less overview.

5. Discussion

In this work, following a user-centred design approach, we designed a landmark-based pedestrian navigation system for smartwatches. Specifically, users were involved earlier in the design process to collect their opinions and feedback regarding the initial interface design. This helped to confirm and identify good features of the initial interface (e.g. a combination of map view and direction view, track-up orientation), as well as prompted subsequent refinements to its deficient aspects (e.g. missing of overview information, support for the first path segment). Both helped to ensure that the revised user interface meets users expectation and has a good usability, as can be seen from the second field experiment. This illustrates that user-centred design is a powerful tool in designing this kind of systems. Its iterative characteristics and involvement of users in the design process help to identify good design alternatives and discover potential interface problem at a very early phase, which will ensure a good usability of the system developed.

From the two field experiments, we can observe that the combination of map view and direction view was considered as very useful. Participants used the direction view for clear instructions, whereas the map view provided an overview of the surrounding environment. Using a track-up orientation on the map view can be also concluded as a good choice, especially since there is no manual or mental rotation required by the user. The approach of showing the map from the current location of the user until the next decision point proved to be viable, and participants did not feel that they required any manual zoom or scroll functionality. While the display of a smartwatch is much smaller than the screen of a smartphone, participants had no problems in reading the map or interpreting the instructions. Including landmarks was perceived to significantly reduce the workload (lower NASA RTLX scores), and was clearly preferred by all participants. This confirmed the findings of many existing studies on landmark-based navigation systems designed for smartphones (Fellner, Huang, and Gartner 2017; Li et al. 2014). Landmarks provided clear reference points which participants used to orientate and reassure themselves. Participants felt that the vibrations before decision points allowed them to not check their smartwatches that often, but rather rely on the tactile feedback when actions were necessary. Results of both field experiments also confirm that the five principles introduced in Section 3.1 are useful guidance for route map design on smartwatches, especially regarding the general way how the route, decision points and landmarks should be considered and visualized.

The accuracy of the current location and bearing was found to be lacking by some participants. Their values were retrieved periodically from the GPS of the paired smartphone (since the used smartwatch did not support GPS itself) and sensors (magnet field sensor and accelerometer) of the smartwatch. The accuracy of the location plays a crucial role for the functionality of the application because the shown map and direction views depend on this information. Furthermore, the information is also used to trigger vibrations at appropriate locations. If the retrieved location information is not accurate, vibrations may be triggered at the wrong times and locations. It is thus important to consider and handle inaccuracies, since the accuracy of the location and bearing information can vary dependent on the environment as well as the used device. Map matching techniques as well as dead-reckoning methods might provide some hints on this aspect.

It is also interesting to see that the perceived workload (i.e. NASA RTLX, the overall score of 9.48) reported by the participants in this study seems to be lower than those reported in previous studies with map-based pedestrian navigation systems on smartphones. For example, in Rehrl et al. (2014), the perceived workload is between 12 and 13. This might suggest that navigation with smartwatches might lead to a lower workload than that with smartphones, as smartwatches provide a hands-free navigation guidance. More research should be done on this aspect to see whether this is a general case.

While this study shows that landmarks are beneficial to be included for smartwatch-based pedestrian navigation, a critical question is still on landmark selection. In this work, we made use of existing findings on this aspect (Sorrows and Hirtle 1999; Elias and Paelke 2008; Richter and Winter 2014; Bauer, Müller, and Ludwig 2016), and manually selected landmarks for each route. It is important to investigate how the selection process can be automated, making use of existing datasets (Point of Interest data in OpenStreetMap) in an urban environment. This will require to assess the visual, structural, and semantic salience of potential objects in the environment (Sorrows and Hirtle 1999; Raubal and Winter 2002).

In the current work, the participants for both field experiments were mainly young people between 24 and 33 age old. This group of users are more familiar with smartwatches than other age groups, e.g. elderly. Therefore, it would be very interesting to see whether the experimental findings are still applicable to other age groups. It might be also very useful to see how smartwatches can be employed to provide navigation guidance to support visually impaired people.

Another limitation of the study should be also mentioned. In the second field experiment, we captured when and where the screen of the smartwatch went on or off. The original idea was to see how often participants needed to use the navigation system to get route instructions. However, the use of vibrations at each decision point in the prototypes (i.e. features of the prototypes) brought biases to the captured data. These biases make it difficult to link the screen-on data with decision errors, complexity of the route and interface, and the perceived workload. Further research should be done to analyse these links.

6. Conclusion and future work

It is nowadays common to use navigation systems via smartphones for navigation purposes. Recent years have seen the rise of wrist-worn devices like smartwatches, which might be a good alternative to support pedestrian navigation. However, the limited screen size of smartwatches imposes challenges regarding the design of smartwatch-based pedestrian navigation systems.

This paper illustrated how user-centred design can be applied in designing landmark-based pedestrian navigation systems for smartwatches, considering the small screen sizes as well as the very limited interaction capacities of these wrist-worn devices. Two field experiments were implemented to identify users opinions and feedback of the initial user interface, which were then carefully considered to develop a revised user interface. The key features of the revised user interface include: a combination of map view and direction view, track-up (instead of north-up) orientation of the map view, inclusion of landmarks at decision points, and vibrations before decision points to prompt turning actions. As can be seen from the second field experiment, these features were perceived as very useful for supporting pedestrian navigation via smartwatches. In other words, these features help to address the challenges brought by the small screen sizes as well as the limited interaction capacities of the smartwatch. The results also illustrate that the iterative characteristics and early user-involvement of the user-centred design approach are very useful in designing this kind of systems, as it can help to discover potential design problem at an early stage, and ensures a good usability of the system developed.

It is also interesting to see that the perceived workload reported by the participants for the proposed smartwatch-based navigation systems seems to be lower than those reported in previous studies on smartphones. This further confirms that smartwatches have a high potential to support pedestrian navigation.

This work represents a solid base for further exploring smartwatch-based pedestrian navigation. Obviously, the proposed user interface can be further refined and adjusted, and a more comprehensive field experiment with sophisticated routes can be conducted. Particularly, the following aspects could be further explored: using different vibration patterns for conveying turning directions, inclusion of landmarks along the route (i.e. landmarks that are not directly around the decision points), and automatic selection of landmarks. Meanwhile, as more and more people are carrying smartphones and wearing smartwatches at the same time, it is interesting to explore how the user interfaces of these devices can be designed to allow cross-device interaction to achieve good user experiences in navigation (Huang et al. 2018).

Notes

1. A related issue to this is: how many landmarks should be visualized to provide effective and efficient navigation guidance? Bauer, Müller, and Ludwig (2016) provided some insights on this aspect, and showed that depicting one landmark leads to faster self-localization, compared to using four landmarks.
2. In this street name-based prototype, we also did not differentiate non-subsequent and subsequent turns in the direction view. However, this difference is really minor, and only one participant took advantage of it in the second filed experiment.

3. The reason for this unclear pattern is unknown and requires further study. It might be due to the differences in terms of the general shape and complexity of the routes. Route 1 seems to contain longer route legs, and might be generally easier for people to follow regardless of the prototype used. Learning effect might be another potential reason. For Route 1, participants of both prototypes might be still in a learning phase to get familiar with the small screen interfaces, while for Route 2, participants of the landmark-based prototype might start to take benefits of the included landmarks.

Author Contributions

This paper is based on the Master Thesis of Martin Perebner (MP), supervised by Haosheng Huang (HH). MP and HH conceptualized the work, and wrote the paper. Georg Gartner as the Head of the research group oversaw the whole process.

Disclosure statement

No potential conflict of interest was reported by the authors.

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