Pedestrian Navigation and GPS Deteriorations: User Behavior and Adaptation Strategies

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ABSTRACT

Mobile pedestrian navigation apps depend largely on position information, usually provided by a Global Position System (GPS). However, GPS information quality can vary due to several factors. In this paper, we thus investigate how this affects users via a field study (N=21) that exposed pedestrians to no GPS coverage, low accuracy and delayed GPS information during navigation. We found that their navigation performance, their trust in the apps and their experience were all negatively affected. We also identified user strategies to deal with GPS-deteriorated situations and user needs. Based on our findings, we derive several design implications for pedestrian navigation app to better deal with GPS-deteriorated situations. In particular, we propose four adaptation strategies that an app can use to support users in GPS-deteriorated situations. Our findings can benefit designers and developers of pedestrian navigation apps.

CCS CONCEPTS

• **Human-centered computing → Empirical studies in HCI**; *Ubiquitous and mobile computing systems and tools*;

KEYWORDS

Pedestrian navigation, GPS quality variations, location information, mobile map-based interfaces

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1 INTRODUCTION

Mobile devices nowadays are capable of determining their position quite well using sophisticated technologies such as global navigation satellite systems (GNSS) receivers supporting multi-constellations, various sensors as well as enhanced location calculation and sensor fusion algorithms. Besides improving traditional map-based turn-by-turn navigation for pedestrians, this development has also enabled new modalities for pedestrian navigation support, such as vibrotactile [33], gaze [14], public displays [39], vibro-gaze [15] and augmented reality [36]. However, common mapping services (e.g., Google Maps) are still the most widely used approach for pedestrian navigation. Despite improved positioning accuracy and the ubiquity of mobile devices, navigation in new environments using mobile maps remains challenging [11, 38].

The quality of the navigation support is good as long as the quality of the location information is good. Although "accuracy" is often used to describe location quality, it is a multi-faceted concept and can include various facets such as coverage, delay, accuracy, granularity and update rate. While the quality of location information available for the pedestrian navigation applications has improved over time, there are still situations where the quality of location information substantially decreases or where no information is available at all. This can happen, for example, in adverse weather conditions, when being near high-rise buildings or when being exposed to strong electromagnetic fields. When such GPS-deteriorated situations occur, navigation apps can no longer rely on good location information. How users of these apps cope when facing such situations has not been studied well. Information on how users are affected by these situations, how they deal with them and what their specific needs are could provide useful insights for designing navigation applications and mobile map-based interfaces that better support users in such situations.

In this paper we thus investigate: (a) how GPS-deteriorated situations affect pedestrian navigation users, (b) how users usually deal with such situations and what strategies they use to cope with them, and (c) how to design pedestrian navigation apps that better support users in GPS-deteriorated situations. We conducted a field study (N=21) that exposed users to three types of GPS-deteriorated situations (no coverage, low accuracy, and delay) to find out whether they perceive these situations as problematic, how they are affected, how they deal with them, and what needs they have in such situations. Our results indicate that GPS-deteriorated situations are problematic to users and affect navigation performance, user experience and the trust in the apps.

2 RELATED WORK

Location sensing

Pedestrian navigation services usually rely on GNSS such as the Global Positioning System (GPS) and the Russian Globalnaya Navigazionnaya Sputnikovaya Sistema (GLONASS) [31] to obtain positional information that is required to localize and guide pedestrians in outdoors. In addition to GNSS, cellular networks [13], WiFi [24], Inertial Measurement Units (IMUs) [30] or the built-in sensors of a smartphone (accelerometer, magnetometer, compass) [31] have been used to localize people and devices in outdoor environments.

Quality of location information

The behavior and performance of all sensor types commonly used for outdoor localization can be affected substantially by many factors beyond the control of designers and users. GNSS signals are often subject to fading due to attenuation or multipath reflections, particularly in urban canyons and roofed structures [5]. GNSS accuracy is also affected by body-related issues such as different hand grip styles or body placement of the GNSS receiver [5]. Furthermore, the device type can affect accuracy: the same GNSS receiver chip installed in two different phones may produce different levels of accuracy due to device differences [20]. Cellular network based localization is affected by various factors such as properties of the transmission medium, interference from other objects and nearby cells, environmental factors [27], cell size, cell density [29], and blocked line of sight. WiFi-based positioning is subject to effects caused by environmental changes, signal degradation, the orientation of the mobile device, multipath reflections, human presence, the device used, or the presence of small objects [7, 19]. The quality of the output from inertial sensors is affected by the quality of the sensor hardware, accumulated drift, magnetic interfaces and the phone's position on the body [26, 40]. Consequently, when used in real-world settings, these sensors will thus produce location information of varying quality. In some cases, it might be possible to predict when/where they occur (e.g., urban canyons) while in others (e.g., human presence/crowd density) it is not. Location information can thus be degraded in several ways. It can be unobtainable (no coverage) [41], inaccurate [1, 10, 25], imprecise [1, 4], delayed (not fresh) [35] or conflicting/ ambiguous (contradictory readings from different sensors) [9, 45] at times.

Current approaches to address such variations in the quality of location information mostly focus on sensors or the processing that calculates location information from raw measurements. Common strategies of this type include improving the sensor technology (e.g., by integrating better clocks into GPS receivers), fusing sensor data (e.g., by combining WiFi and GPS data) or developing better algorithms (e.g., by including contextual factors to eliminate unreachable positions). Due to these efforts, the average quality of positional information has continuously been increasing over recent years enabling new approaches such as pedestrian navigation support via vibrotactile stimulation [32] and Augmented Reality [3]. These approaches require much higher location quality [3] and will, therefore, be affected strongly by quality fluctuations. As discussed above, despite improved sensing technologies there still are and most likely always will be situations where users and apps are facing low-quality location information or a complete lack of such information.

Pedestrian navigation and low quality location information

There is a large body of work that investigates pedestrian navigation and wayfinding in standard usage scenarios. However, pedestrian navigation under location information quality variation has received little attention so far. Dearman et al. [10] discovered that there is a significant benefit in revealing the error of location. Burigat and Chittaro [6] found that conveying location errors using colored street segments was perceived as being beneficial by users and resulted in lower workload. Ranasinghe and Kray [34] found that users' perceptions and preferences regarding location uncertainty visualizations could vary between users of the same culture as well as across cultures. Askenov et al. [2] reported that the additional visual demand caused by raising users' awareness of different aspects of location uncertainty was perceived to be worthwhile by users [2]. They also discovered that the importance of different characteristics of this awareness varied between users and depended on the user profile. Furthermore, they reported that the importance of this awareness is high when the quality of location information is low (i.e., the importance increases in problematic areas) [2]. Goodchild et al. [28] reported that the way in which uncertainty is visually depicted influences judgments of positional uncertainty [28].

Summary

In summary, there is thus ample evidence that the quality of location information can vary and may affect users of pedestrian navigation applications. However, there is no clear empirical evidence on how exactly they are affected. Therefore, systematic research is needed to understand if and how GPS-deteriorated situations affect pedestrian navigation users, how they deal with such situations and what their needs are. We argue that such research could reveal useful insights for designing navigation applications and mobile map-based interfaces that provide improved navigation support in such situations. In addition, the strategy of coping with quality variations at the navigation app level complements the common strategies of dealing with this issue at the sensor or algorithmic level.

3 STUDY

Our overall research goal was to answer the following research questions: **(RQ1)** *Do GPS-deteriorated situations affect pedestrian navigation users, and if so, how?* In particular, we wanted to find out how the users' performance, feelings, and trust in the application is affected. **(RQ2)** *How do users deal with these situations?* We were specifically interested in finding out what strategies users apply to deal with GPS-deteriorated situations and what their needs are when facing those situations. **(RQ3)** *How to design pedestrian navigation apps that better support their users in GPS-deteriorated situations?* This question relates to identifying ways to improve the navigation application itself so that it provides better support to users in situations arising from low quality location information. In order to answer these three research questions, we designed and conducted a field study with follow-up interviews. We used the results to derive design implications for pedestrian navigation apps.

Design

In the field study, we asked participants to navigate in an unfamiliar area along a predefined route using a pedestrian navigation app on a mobile phone. The route was fixed to ensure comparability between participants. An experimenter walked behind the participant and used a remote control app (experimenter app) to manipulate the quality of the location information on the participant's phone to simulate GPS deteriorations. Figure 1 depicts the study area, the predefined route and where location information was manipulated (control regions). In a pilot test with five participants, we

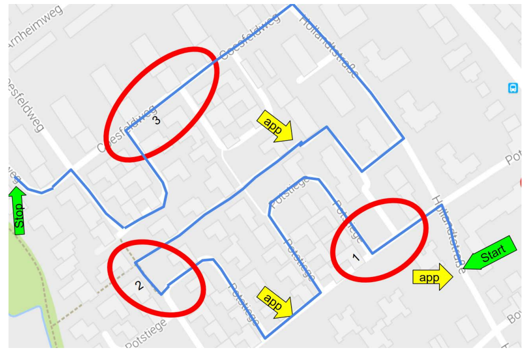


Figure 1: Study area: The regions marked in red are the regions where the GPS deteriorations were applied. We changed the navigation app in the user's phone at the points marked by the yellow arrow.

originally exposed them to seven different types of GPS-deteriortations but found that this caused too much confusion. For the main study, we, therefore, decided to expose participants to only three types of GPS deteriorations, which had been identified by Willis [44]:

- where GPS signal availability is weak or non-existent in the environment (no coverage condition),
- slow and unpredictable temporal characteristics of GPS signal (delay condition), and
- inaccuracy in GPS signals identification of location (low accuracy condition).

In the no coverage condition, the user's GPS signal was blocked while they were in the designated region (until they exited it). In the delay situation, a location delay of 15 seconds was introduced, and in the low accuracy situation, we reduced the location accuracy to 20m. All three types of deteriorations were triggering by experimenter via the remote control app.

We selected a study area (Figure 1) on the outskirts of AnonymousCity for several reasons. We wanted to ensure that the area was unfamiliar to most people, yet quick to reach for logistical reasons. In addition, we wanted it to be quiet to ensure repeatability and to reduce interference by external factors. Furthermore, we looked for an area with little traffic to ensure the safety of the participants. Since we were exposing them to potentially challenging situations, this was an important factor, which we further ensured by the continuous close observation by the experimenter. In addition, we chose the area since the quality of the GPS signal was generally good throughout. The reason behind this was that we were using the GPS signal as 'ground truth' that we then applied the deteriorations to in the designated areas. If the quality of the GPS signal in the study region had fluctuated a lot, there would have been the danger of this introducing additional deteriorations and affecting the app behavior across regions and participants. Finally, we chose a region where we could plot a route that would result in three similarly complex segments, which we required to implement a latin square design in order to minimize potential order effects.

We selected three regions along the route in which the user was exposed to the three GPS deteriorations: region 1 to 3 (marked in red in Figure 1). Region 1 had two right turns, where the user had to take the second right turn. Region 2 had a T-junction and small four-way junction. Region 3 had two left turns, and the user was expected to take the second left turn. We developed a simple navigation app similar to Google Maps for the navigation task. We created three versions of this app, which users could distinguish by the three different colors we used for the frame and opening background. The app was changed at three different locations of the route (marked by the yellow "app" arrow in Figure 1) to reduce learning effects. We informed users at the beginning that they were going to use three different apps.

Materials

We gathered demographic data and information about navigation app usage via a pre-study questionnaire. A set of pre-designed guiding questions drove the semi-structured interview with participants after they had completed the navigation task. For the navigation task itself, two Android 6 smartphones running Android 6 were used: a Samsung Galaxy S6 for the participant and a Google Nexus 5 for the experimenter. A mobile wireless UMTS modem (Huawei E585) provided a WLAN connection between the phones and internet access (for loading the background map and communication via the Nearby API). A GoPro Hero 4 camera was strapped to the experimenter's chest and recorded the user from behind them. Two custom apps we developed were used for the navigation task (on user's phone) and for remote controlling the GPS deteriorations (on experimenter's phone). A third-party application, ADV Screen Recorder, recorded the screen of the user's phone, the face of the user and audio of the user. After the experiment, we used VLC for the parallel video playback of the screencast and video footage on a large screen. Post-experiment interviews were recorded using the audio recording feature of a Samsung phone. During the navigation task, the experimenter used a printed map similar to Figure 1, to determine where to apply which GPS deterioration.

Participants

We conducted a pilot study with five participants, which led to a reduction of the number of GPS deteriorations in the final study. The actual study took place with 21 participants (9 female, 12 male, aged between 22 and 38). They were recruited through advertisements in social networks and mailing lists. None of the participants were familiar with the study area. All of them had previous experience in using pedestrian navigation applications.

Procedure

Upon arrival, participants received an introduction to the study and the task and were then asked to sign the consent form and fill out the introductory questionnaire (demographics, smartphone usage information and Santa Barbara Sense-of-Direction Scale (SBSOD)[16]). We also answered any questions that they had. The participant and experimenter then biked to the study site, which was about 1500m away from our lab. Once on site, the experimenter first explained the navigation app and the procedure to the participant, and then let the participant explore the app and ask questions. Afterward, the experimenter walked the participant to the beginning of the route, calibrated the compass of the participant's device, and handed it over to the participant. The participant then started to follow the route (Figure 1) using the navigation application. The experimenter, while walking behind the participant applied the three different types of GPS deteriorations in the regions marked as 1, 2, 3 in Figure 1 using the remote control application in the experimenter's phone. The three types of GPS deteriorations were randomized in the three designated regions using a Latin Square design.

The participant was video-recorded using a camera attached to the experimenter's chest. The phone screen, user's face and audio of the participant were recorded using a third-party application (see Materials Section). The user's actual location, the current time, and the active set of manipulations were logged to a .csv file in the background. At designated points in the route (indicated by the yellow 'app' arrows in figure 1), the experimenter stopped participants and changed the application. He then informed users that they were now using a different app.

After completing the navigation task, the participant and experimenter returned to our lab for a final interview. The screencast of the participant's smartphone screen, face and the captured video footage were synchronously played back on a large screen during the interview so that she/he had a chance to recall and comment on their actions during the interview. At several points during the interview, the video playback was stopped, and a set of questions were asked to probe if participants experienced a problem at these points and to obtain further details. The entire study took about 2 hours (briefing, filling consent forms and questionnaires, biking to the site, experiment introduction at the site, navigation task, biking back and the post-trial interview). Participants received a payment for their time spent on the study. The institutional ethics review board approved the study.

We analyzed the data we collected in the following way. We used the video footage to count the number of stops, the number of wrong turns and the number of questions asked in each region. The speed of the participants and the actual trajectory data were calculated from the logged GPS data of the user's phone using QGIS. We used a simple coding scheme based on the research questions to analyze the interviews. This coding scheme included, amongst others, categories for the apps that users used for navigation, for whether they plan before the navigation, for what apps they used for planning and why, for the users' feelings when facing GPS deteriorations during the experiment and in reality. In addition, there were codes related to strategies used to cope with GPS deteriorations.

4 RESULTS

In this section, we report on the key findings of the study. We first present the demographics and details of the prior experience of users in using pedestrian navigation apps. We then summarize how the GPS-deteriorated situations affected users. Third, we present the strategies users use to deal with GPS deteriorated situations. Finally, we summarize the identified needs of users in these situations.

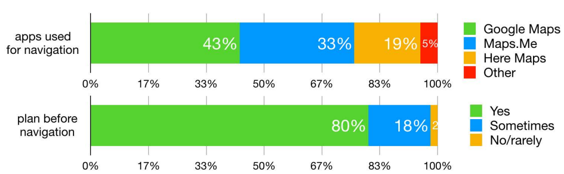


Figure 2: App usage for navigation and planning

Demographics and Prior Experiences

The majority of users use Google Maps for navigation, and there is a trend towards the use of offline maps (*see also* Fgure 2). Users who migrated from Google Maps to Maps.me and Here Maps did so mainly due to the offline feature of Maps.me and Here Maps (although they knew Google Maps has an offline feature). Most users usually plan before navigating, and those who do all use Google Maps for planning. Planning usually occurs on their computer unless they do not have access to it, in which case they use their mobile device. In the planning phase, users also take notes, sketches, screenshots of the map and satellite images depending on where they have to go as a proactive strategy.

Impact of GPS deteriorations

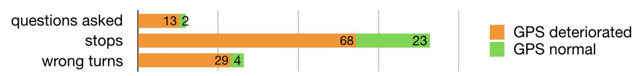
We analyzed the impact of GPS deteriorations on the users along three main dimensions: user performance (number of wrong turns, number of stops, number of questions asked), user experience, and the users' trust in the navigation app.

Performance: Users made more wrong turns, stopped more frequently and asked more questions from the experimenter in GPS-deteriorated regions compared to regions with regular GPS quality (Figure 3a). The number of wrong turns per type of GPS deterioration is shown in Figure 3b. No coverage accounts for the largest number of wrong turns and delay is the second largest. These results also suggest navigating region 2 was more difficult than region 1 and 3.

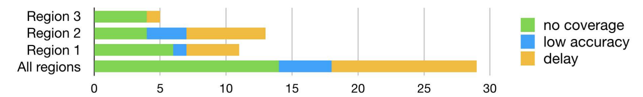
From the video data, we observed that the users slow down in GPS deteriorated regions compared to other regions. We analyzed the trajectories to get a better feeling of where each participant slowed down. Figure 4 shows how the speed of participants varied along the route. The dark areas in the figure indicate where the participants slowed down or stopped. Apart from the spots where we switched the app, participants frequently slowed down in GPS-deteriorated regions.

User experience:We asked users to describe how they felt when experiencing the three types of situations (no coverage, low accuracy, delay) in real life. The results are shown in Figure 3d. It appears that the users are more affected by no coverage and delay situations. Although low accuracy seemed to be the most frequent problem, users did not see it as much of a problem (Figure 3d). Some participants also said how they feel depends on the situation (e.g., P21 "*depends on the situation. If the distance is short like 20 meters, it's not a problem, but if it is like 100m, then it will be annoying. It also depends on if I have time or if I am in a hurry*). Terms users used to describe their experience, besides being annoyed, included being frustrated and being confused.

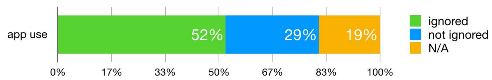
Users' trust in navigation app: We also asked users whether they ignored the navigation app after they had experienced GPS problems. The majority of the users said that they ignored the app after they had experienced problems due to GPS deteriorations. During the analysis, we had noticed a considerable decrease in the number of wrong turns in region three compared to the other two regions (Figure 3b). In the post-study interview, users reported that they relied on their navigation abilities rather than on the app in region three since they had experienced problems previously in region 1 and region 2. However, some users did not ignore the app even after experiencing problems. For some users, this question was not applicable (marked as 'not applicable' in Figure 3c) because they used and trusted their navigation abilities and did not depend on the app. These users referred to the app only occasionally after having used it at the beginning. Consequently, they said the GPS deteriorations did not affect them much because they already stopped depending on the app. Hence, it was not relevant to discuss their trust in the app in GPS deteriorated situations(e.g. P11:"*I usually look at the first part or first landmark and then I follow the route and when I am unsure [...] then I check the phone [...]*



(a) Number of wrong turns, stops and questions asked to the experimenter: GPS-deteriorated regions comparedvs GPS normal regions



(b) Number of wrong turns per type of GPS deterioration per region where the deteriorations were applied.



(c) Percentage of users ignoring the app after experiencing GPS deterions.

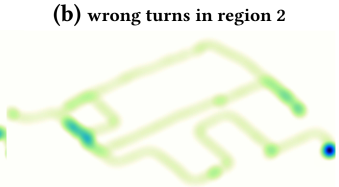
(d) Reported user experience after facing GPS-deteriorated situations.

Figure 3: Impact of GPS-deteriorated situations on users.

(a) wrong turns in region 2

(b) wrong turns in region 2

(c) wrong turns in region 1 and region 3



(d) wrong turns in region 2 and in a GPS normal region

Figure 4: Participants slowed down in GPS deteriorated regions (the darker the color, the slower the walking speed), a, b, c, and d above are speed maps of four randomly selected participants.

Table 1: User strategies in GPS-deteriorated situations

Strategy
Slow down and pay more attention : 100%
Map referencing : 100% *any prominent landmark (e.g. churches, schools)* : 100% *green areas* : 100% *shape of the buildings at the turns* : 95% *famous shops & restaurants (e.g. Mango, Starbucks)*: 95% *color of the buildings at the turns*: 71% *road attributes (name* :90%; *type*: 90%; *width*: 86%; *shape*: 81)% *spatial chunking based on above features* : 95%
Walk back to a known location : 95%
Asking from someone 95% (*last option* : 86%; *first option*: 5%)
Use local information such as you-are-here maps: 14%

just for reassuring or if I can not remember the right thing or if it is too complicated [...] usually it's in my pocket [...] so even I would not usually notice that there is a GPS problem").

User strategies in GPS-deteriorated situations

Based on what users said during the post-study interview, we identified five main user strategies (cf. Table 1) in dealing with GPS deteriorated situations: (i) slowing down and paying more attention until the GPS is back to normal, (ii) ignoring the location marker but keep referencing the map, (iii) walking back to a known location and starting to navigate from there, (iv) asking someone in the street, and (v) using local information such as you-are-here maps or signboards. In the following, we discuss these strategies in more detail.

Slow down and pay more attention until the GPS is back to normal: All users said that they slow down and pay more attention when they experience low-quality GPS situations (Table 1). For example, Figure 4 shows how the speed varies in different regions of some selected participants. They said they slow down to double check, to pay more attention, to wait until the GPS is back, and to adapt to the situation. E.g., P18:"*[...] to double check everything and walk slowly, therefore [...] I keep looking at the app, go a little bit slower and wait for GPS to be back*". We observed this in video data and verified during the post-study interview. For example, P11 and P14 applied this in region 2 and did not make wrong turns.

Ignore the blue dot but reference the map: Users said that in GPS-deteriorated situations, they ignore the location marker (the blue dot) and refer to the map instead. During the interview, we identified two main map objects users often reference in such situations: landmarks and roads/streets. The types of landmarks users said that they would look for are buildings at the turns, color of the buildings, green areas, significant buildings or objects such as churches, schools, monuments, street arts as well as their color, shape, and texture. Users often use street names either to find the correct path or to get back to the correct route after getting lost. The width of the road seems to be an important factor as well since pedestrian navigation often involves walking along regular roads as well as along streets and paths of different width. This was mentioned very often during the interview and seemed to be of considerable importance in GPS-deteriorated situations. The shape of the road was another attribute that users often cited as necessary. For example, after making a wrong turn in region 1, P14 used the shape of the road to avoid making wrong turns again and emphasized the need for the map to represent the road shape correctly. Users often use spatial chunking based on landmarks or road network features. For example, many users said they would count the "number of blocks" until the next turn or "walk until you see X."

***Walk back to a known location and navigate from there*:** Users reported that they often walk back to the last known location or some "significant" location, and then try to find their way from that location when they experience GPS deteriorations. Frequently cited significant locations were crossings, bus stops, and roundabouts. During the experiment, P15, P17, and P18 used this method in region 2 to get back to the correct route after making several wrong turns.

***Asking someone in the street*:** Asking someone is also a strategy that users often use. However, many users would use this as the last option.

***Use local information*:** Some users would also use information from other sources such as you-are-here maps and signboards (P14) when experiencing GPS deteriorations.

User needs in GPS deteriorated situations

We asked participants what type of information a navigation app could provide to better support them in GPS-deteriorated situations and categorized their feedback into four classes (Table 2) : (i) Notification about the problem, (ii) Rendering (iii) More information (iv) Control and offline support.

***Notification about the problem*:** The majority of the participants expressed the need for some form of notification to alert them when a problem with the GPS occurs (e.g., P18:"*If I know that something is wrong beforehand, it will confirm me that maybe I have to stop or I have to adjust*"). During the study, some participants did not pay attention to the app or kept the phone in their pocket; they could thus not have noticed when the GPS deteriorated. Figure 5 shows what type of alerts users preferred for being notified about GPS problems.

Visualization change was the most preferred type of alert compared to sound and vibration. Most participants suggested a change in color, while some proposed a blinking location marker in addition to the color change. The majority of the users emphasized the change in visualization based on the magnitude of the problem; for small problems no visualization change is required. Participants also suggested different visualization changes for different types of issues. They also pointed out possible issues with visualization changes such as misinterpretation and difficulty in understanding. Some users liked vibration alerts. The main reason why they liked vibration alerts is that they can notice the problem even when they are not looking at the phone. Only a few users were in favor of sound alerts and said they could be useful if the user is not looking at the phone. However, they also suggested having an option to turn it off. The majority of users did not like sound alerts and considered them as "confusing" or "annoying." Participants also suggested other types of alerts in addition to the types we proposed. For example, some liked to see an accompanying text explaining what the problem is (e.g., P5: " *maybe, some explanation, for example, 'there is a delay in location updates' together with the visualization change*"). Some also wanted to know the reason for an error or the type of error because the problem can be due to something other than GPS (e.g., a problem in

Table 2: User needs in GPS-deteriorated situations

Notification about the problem: 90%
change in visualization: 90%
(color change: 90%; blinking of the location marker: 81%; different visualizations for different problems) : 81%
vibration alert: 43%
sound alert: 33%
accompanying text: 38%
reason for the problem: 38%
Rendering: 100%
landmark-based instructions : 100%
emphasized landmarks: 100%
simpler apps: 100%
simpler maps : 71%
More information: 90%
building/ house numbers: 90%
images of landmarks: 67%
information embedded in landmarks: 86%
road attributes (name: 90%; type: 90%; width: 86%; shape: 81)%
Control and offline support: 100%
control in choosing options and functionalities : 90%
offline support: 81%

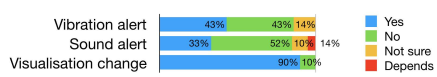


Figure 5: User preferences for how to be notified about GPS deteriorations: visualization change, audio or vibration.

the phone or an internet problem). They pointed out that knowing the reason is useful in adapting the behavior to the actual problem. Participants also pointed out that too many notifications could imply that the app is problematic instead of GPS. The majority of participants was in favor of enabling users to configure which types of notifications they receive.

***Rendering*:** During the post-trial interview, users indicated several aspects related to rendering as being beneficial in GPS-deteriorated situations: (a) emphasizing prominent landmarks along the route, (b) simpler navigation apps designed for pedestrian navigation, and, (c) simpler maps.

Emphasizing prominent landmarks: All users highlighted the need for emphasizing landmarks (by coloring or by blinking) along the suggested route in general and in GPS-deteriorated situations (e.g., P20: "*If the navigation system fails, if the current position is not accurate or visible, then probably seeing the landmarks in color beforehand, then you can find the correct route*"). Highlighting landmarks seems to make it easier to find the correct route (P17), to lessen mental workload and reduce the need for zooming (e.g., P20: "*Otherwise, I have to mentally process [...], but if it is a landmark then it would be more easy for me [...] I prefer to see the landmarks highlighted rather than forcing me to zoom in and out*"). Showing landmarks in the surrounding areas can also help reorientation (e.g., P11:"*in such situations, it might be helpful in my closest area there might appear to have some landmarks [...] might help to orient myself* ").

Simpler navigation apps designed for pedestrian navigation: All users said they used audio directions only while driving but not for pedestrian navigation. They instead use the location marker (the blue dot), the mobile map and the suggested route (the path shown by on the map)(e.g., P11:"*for walking? No, I never switch on the navigation. I just use the blue dot and the map*"). All users preferred landmark-based instructions over instructions using metric distances. Participants also pointed out that distance-based instructions can be misleading when there are delays in the GPS signal or when there are many options (e.g., many turns close to one another).

Simpler maps: Many users indicated the need for "different" maps tailored for pedestrian navigation. For example, some preferred maps which show the buildings at the turns or corners to appear in their original color in the map. Some preferred maps that show important landmarks without showing "everything" (e.g., P7:"*It would be good if the map only shows what are important for pedestrians [...] such as buildings at the turns [..] green areas [...] I don't need to see everything*").

***More information*:** The majority of users requested additional information to help them in GPS-deteriorated situations. Building numbers (or house numbers) were considered very useful in GPS-deteriorated situations. Users also thought accompanying images would be beneficial. However, many users also emphasized that they should either be provided on demand or users should be given the option to turn them off (e.g. P18: "*pictures [...] of features that are significant or have historical importance [...] if can have picture when you click on a building or an icon, they will be helpful*"). Most users also requested a clear representation of the road width, type (e.g., walking path, bicycle path), and the shape of the road. They said that this information could help, for example, to decide between near-by similar looking alternatives (P4: "*[...] and shape [...] when there are close similar-looking alternatives*"). Many users wanted to have access to information about the issue causing the GPS deterioration or about landmarks (e.g. P18: "*If the app says, for example, suppose I recognize whether by blinking or by text that my signal has stopped, then, when I click on the icon and see some information, regarding the error or on navigating further that would be excellent [...] other types of information, for example, attributes attached to the map symbols, where users can click on them and see more information would be good. Otherwise, it would crowd the interface. If I know that this app has information embedded within icons, then I know that I can click on them and get information and compare with the real environment*").

***Control and offline support*:** The majority of users was keen on being able to choose the options, functionality and the look and feel of the app in different ways. For example, P16 noted that it "*could be annoying, but if you are in a forest and you want to keep your hands free, and your phone is in your backpack so you will not feel vibration, then sound would be the best. [...] depends on the situation*"). Participants emphasized that additional information such as pictures attached to landmarks should be available "on demand" (see "More information"). Similarly, the use of color for emphasizing prominent landmarks was suggested to come with an option to turn it off (e.g. P16 "*[...], but I also understand that maybe this could be too complex if there a too many colors. It would be good if there is an option to turn color on or not*"). Participants also suggested using different maps for different situations and for different users (e.g., P2: "*I doubt using the same type of map always [...] for all users [...] for all situations is a good idea*"). Many users reported that one of the main problems they face is not having a data connection (especially when they travel to other countries), and they pointed out the need for offline availability of the map and the navigation app.

5 DISCUSSION

In this section, we discuss our key findings and how they can help to design navigation apps and mobile map-based interfaces that support users in GPS-deteriorated situations. We also outline the limitations of our studies.

Impact of GPS-deteriorated situations on users

Our study revealed that the users' navigation performance, experience, and trust in the app are negatively affected by GPS deteriorations. They make more wrong turns, take more time for navigation and feel annoyed, confused or frustrated when experiencing such situations. Many users started ignoring the app after experiencing GPS deteriorations. Users were mainly affected by no coverage and delay situations while low accuracy seemed to be a lesser problem. The way users can be affected also depends on the situation (whether they are in a completely unknown area, know the local language, or are in a hurry). Furthermore, different users can be affected differently depending on various factors such as the navigation techniques they use. These results imply that navigation apps should be designed in a way to better support users in GPS-deteriorated situations to avoid user frustration and ignorance of the app.

User strategies

We identified five main strategies users apply in GPS deteriorated situations (**user strategies**): slowing down and paying more attention; ignoring the location indicator but using the map; walking to a known location and reorienting from there; asking someone, and looking for locally available information. The first three strategies are more frequent and preferred by the majority. Most of the time, these strategies are used in combination, and what strategies are applied depends largely on the situation and the users themselves. Therefore, there is no strategy that universally works best in any context.

User needs in GPS deteriorated situations

Users were keen on receiving notifications about GPS deteriorations, on having prominent landmarks along the suggested route highlighted, and on support for offline operation. They also wanted to see simpler apps and maps tailored explicitly for pedestrian navigation (e.g., including building colors, building numbers at turns and prominent buildings), and to have more information available on demand.

Design implications for navigation apps

Based on the user strategies and needs in GPS-deteriorated situations we can derive a number of design implications for navigation apps.

Map and data quality: Our results highlight the significant role landmarks play for pedestrian navigation when faced with GPS deteriorations. On the one hand, this finding mirrors result for 'standard situations,' where landmark-based navigation instructions are known to be highly effective [8, 12, 17, 21–23, 37, 42]. On the other hand, the beneficial effect of including landmarks seems to be even more pronounced in GPS-deteriorated situations. Embedded landmarks with on-demand information such as photographs were considered especially helpful in GPS-deteriorated situations. The same was true for road attributes (such as type, width, shape, usage rules). Thus the results imply that features such as panoramic photographs (StreetView), colors and shapes of buildings that some common map services (e.g., Google Maps) provide are particularly useful in GPS-deteriorated situations.

Hence, our results make a strong argument for maps with a high level of detail for features such as buildings and roads. In addition, the outcomes of our study provide an argument for combining geometrical and basic thematic information with (current) photographs of real-world entities. If such information is available (and can be downloaded for offline operation), users can better cope with GPS deteriorations, e.g., by choosing the level of granularity of information they need based on their preferences, needs, strategies, and situations.

Adaptation strategies: Based on the results of our study, we propose four adaptation strategies that the navigation apps can incorporate to better support pedestrian users in GPS-deteriorated situations : (a) notification about the problem; (b) emphasizing landmarks along the suggested path; (c) displaying landmarks based on location accuracy; and (d) asking the user to slow down and pay more attention to their surroundings.

Navigation apps can notify users about GPS deteriorations (e.g., based on metadata obtained from GPS receivers) in different ways. Visualization changes are one promising option such as changing the color of the location indicator or uncertainty area or blinking the location marker. It may make sense to use different visualizations to communicate different types of deteriorations. For example, an app could use a blue circle to indicate low GPS accuracy, a red dot for a delay and a blinking red dot for no coverage. In previous work, we developed guidelines for modifying the visual variables of the existing location uncertainty visualizations to align the level of accuracy to perceptions of users [34]. Designers can use these guidelines to adapt visualizations to location quality. An app could also take into account the magnitude of the problem when alerting the user: it only needs to alert the user when the extent of the problem actually could affect the current task. A further notification option is to textually describe the type of error or the reason that caused it, which might help users in deciding how to best respond. For example, if a sensor failure is the reason for an error, it does not make sense to move to a different location for better reception.

A second promising adaptation strategy is to highlight landmarks along the suggested path, e.g., by using a specific color, from the start. Users indicated that this would make it easier to navigate and reduce the mental workload in GPS-deteriorated situations. Providing additional on-demand information for landmarks (e.g., photographs of the building) is also desirable. A related adaptation strategy would be to display landmarks based on the quality of location information. For example, if the accuracy falls below a specific threshold or if a no coverage situation occurs, a navigation app could create a buffer around the last known position of the user. It could then display landmarks inside this buffer to help users determine where they are. Photographs of those landmarks (such as the next three landmarks) could be displayed at the bottom of the screen to help with this process.

For the second and the third adaptation strategy, it might also be helpful to design applications that better connect planning and navigation phases. Besides supporting offline mode, such an approach would also facilitate the selection of suitable landmarks, i.e., those of relevance to the individual users. Another (simple) adaptation strategy that navigation apps could employ would be to just ask users to slow down and pay more attention to their surroundings. Similarly, a navigation app could also instruct users to go to a specific location (based on the last known location) and to then try to reorient themselves.

***Empowering users*:** During the experiment and the interview, we discovered that the strategies, needs, and preferences of users when they face GPS deteriorations vary a lot. It is a known fact that individual differences (for example, regarding spatial abilities) affect navigation performance and strategies [18] in standard usage scenarios. Our experiment highlighted their particular relevancy in GPS-deteriorated situations. In order to support different users in such challenging situations, it makes sense to not only incorporate adaptation strategies into navigation apps but also to facilitate far reaching customization or app configuration. This includes providing various map-based interfaces, when and how users are alerted to GPS deteriorations and what adaptation strategies are applied.

***Offline availability*:** The lack of a data connection can affect adaptation strategies (e.g., unavailability of maps a certain scales) and other functionalities (such as using GSM cells to help localization), and thus reduce support to users in GPS-deteriorated situations. Consequently, research on offline operation can also benefit users to cope with such situations. Existing approaches in this area include opportunistic localization [43], smart caching and ad-hoc networking. In addition, the investigation of adaptation strategies tailored to offline use is another interesting option for future research.

Limitations

In order to control various factors, the study used a somewhat artificial scenario, which might have affected user behavior. For example, users experienced frequent experimenter interventions and had to use a predefined, fixed route. In reality, users might have updated their planned path on the fly after a wrong turn rather than backtracking to make sure that they get every turn right.

The study was conducted in a site away from the city center due to the reasons described in the study design section. Therefore, if the study had been conducted in a busier and more urban area, we might have seen more wrong turns and other strategies. However, we tried to cover navigation in more urban areas during the post-trial interviews. In addition, we only used a single route due to logistical reasons. Though we subdivided it into three sub-routes, a broader selection of routes (longer or more complex ones) could have resulted in different outcomes. Furthermore, the majority of the participants were university students and employees. If a wider audience was used, a broader view of how low-quality location information affects pedestrians could have been obtained. Finally, we used the GPS-sensor on the mobile device as ground truth in our study. If the quality of the location sensed by the GPS receiver had varied, this would have affected our study. For example, we could have applied a deterioration to an already deteriorated GPS signal. However, neither our pilot tests nor an informal screening of the video footage and the GPS tracks provided any indication that this was the case during the study.

6 CONCLUSIONS

In this paper, we investigated whether situations arising from low-quality GPS information have an impact on users of pedestrian navigation apps. Our three main contributions are: (1) a better understanding for how GPS deteriorations affect pedestrian navigators; (2) the identification of strategies people use to cope with such situations; and (3) a set of design recommendations for navigation apps to better support users in GPS-deteriorated situations. In our study, we found that user performance and feelings are negatively affected by GPS deteriorations. Users make more wrong turns, take more time for navigation and become frustrated or annoyed when facing such situations. We also identified five common strategies people use to deal with such situations. From these strategies and reported user needs, we derived design implications for pedestrian navigation apps to better support people facing GPS-deteriorated situations. In particular, we proposed four adaptation strategies that an app can use to support users in GPS-deteriorated situations. We highlighted the benefits of high-quality maps with on-demand information and of navigation applications that connect the planning phase and the navigation phase. In addition, we pointed out why providing broad customization options and a high degree of control to users is particularly important in GPS-deteriorated situations. In the future, we will realize and test some of the proposed adaptation strategies in practice. We also plan to investigate the impact of other types of deteriorations of positional information (such as conflicting information). Furthermore, we are interested in how pedestrian navigators perceive the quality of orientation information and the impact of orientation information quality on users.

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