Schematic Maps and Indoor Wayfinding

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Abstract

Schematic maps are often discussed as an adequate alternative of displaying wayfinding information compared to detailed map designs. However, these depictions have not yet been compared and analyzed in-depth. In this paper, we present a user study that evaluates the wayfinding behaviour of participants either using a detailed floor plan or a schematic map that only shows the route to follow and landmarks. The study was conducted in an indoor real-world scenario. The depictions were presented with the help of a mobile navigation system. We analyzed the time it took to understand the wayfinding instruction and the workload of the users. Moreover, we examined how the depictions were visually perceived with a mobile eye tracker. Results show that wayfinders who use the detailed map spend more visual attention on the instructions. Nevertheless, the depiction does not help to solve the task: they also needed more time to orient themselves. Regarding the workload and the wayfinding errors no differences were found.

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1 Introduction

Maps are the main means of displaying information during a wayfinding task [22]. However, these depictions can vary a lot in terms of details, scale, etc. [13]. Schematic maps, i.e. maps that only contain information like the route to follow without a detailed depiction of the environment, are discussed as an adequate representation to convey wayfinding information [9]. In this context, it is still an open question whether these maps contain enough information to solve a wayfinding task and how these maps are perceived - especially in indoor environments:

> "Mobile maps can differ in scale, content, and style. As a result, the effectiveness of different types of maps (ranging from sketch or schematic map to topographic map or other detailed map) for indoor route communication should be evaluated. However, little work has been done on that." [13, p. 312]

Therefore, we addressed the research question whether schematic maps are an efficient means of presenting wayfinding information compared to commonly used detailed map depictions. For this purpose, we used a mobile navigation system in a real-world indoor scenario. To gain a deeper understanding of the visual perception of the different map designs, we moreover analyzed the gaze behaviour of participants with a mobile eye tracker. The remainder of this paper is structured as follows. First, we give an overview of the related work concerning schematic map design and mobile eye tracking during a wayfinding task. Then, we describe our experiment followed by the results. Lastly, we discuss our findings and future work.

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2 Related Research

2.1 Wayfinding and Schematic Maps

Wayfinding is the part of navigation that requires substantial cognitive processes and spatial reasoning to orient oneself [22]. For this purpose, wayfinders often search for salient objects, i.e. landmarks in their environment that help to identify their own position relative to these points [11]. Therefore, a wayfinding aid should help the user to find these objects. Consequently, we included landmarks in our map designs. Moreover, we conducted a prestudy to identify suitable objects.

The wayfinding task can basically be solved without an aid, e.g. with the help of the cognitive map of a person [1]. However, especially in unfamiliar areas or if the destination is not known, persons need the help of an aid [35]. In this context, maps are the most common means of presenting spatial information [22]. As already pointed out, these depictions can vary a lot in terms of displayed content, especially in indoor environments [13], which are the focus areas of this study. However, there are no real design guidelines for the creation of wayfinding maps [18]. Consequently, a framework is missing that informs which elements should be presented to solve a specific wayfinding task under certain circumstances [8]. In this context, schematic maps are often discussed as an adequate presentation of wayfinding information [9, 20]. However, to the best of our knowledge, these depictions have not been compared and analyzed in-depth yet. These maps abstract the depiction and try to convey only the information needed for wayfinding. Commonly, this includes the route to follow and landmarks [16]. In contrast to this, detailed maps depict the environment in much more detail. Every possible path is visualized and more information about the environment is given. In indoor environments for instance, rooms, staircases and the closing direction of doors are often presented (see e.g. [24]).

Our research focus lies on displaying different map depictions with the help of a mobile navigation system. Previous studies in these research areas show that especially landmarks should be depicted more clearly in mobile map designs to support wayfinding (see e.g. [4]). Moreover, it is once again recommended to simplify map depictions to avoid that wayfinders focus on interface elements that are not immediately relevant for their current task [29].

2.2 Eye Tracking in the Field of Wayfinding Research

It is common to analyse the time it takes to accomplish the task (see e.g. [34]) or to measure subjective feelings like the experienced workload (see e.g. [28]) to evaluate mobile navigation systems. We additionally used a mobile eye tracker to analyse the gaze behaviour of the participants. This variable allows to analyze cognitive processes during a wayfinding task [15]. Although it is relatively common to analyze gazes in wayfinding research, this measurement method has some drawbacks. The studies are often conducted in the lab, mainly due to the complications caused by direct sunlight [10]. Since the post experiment annotation process is often cumbersome, frequently small sample sizes with less then 20 participants are used [7]. Studies in indoor environments are rare, only Schnitzler et al. [30] analyzed the use of paper and digital maps in this context. Their results showed no differences between the two depictions.

To overcome all of this research gaps, i.e. small sample sizes and scarce indoor field studies, we conducted a large scale user study with 118 participants in a complex indoor area. The participants used a mobile navigation system and accomplished a wayfinding task in the field.

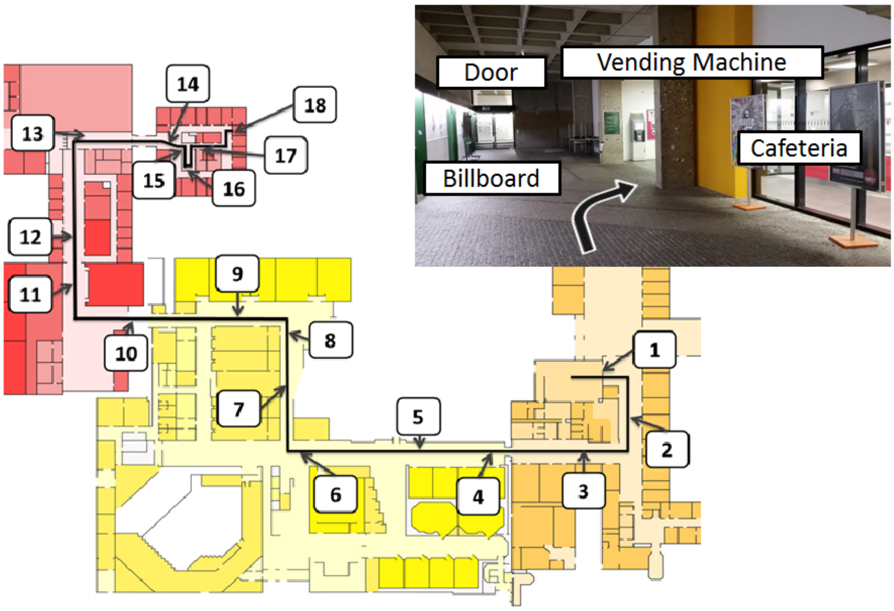

Figure 1 Test route with different colours representing different buildings. Arrows indicate where the participants received new navigation instructions. The example illustrated step 2 with predefined landmarks for the prestudy.

3 Study

In order to address our research question how the wayfinding behaviour differs if schematic maps are used compared to detailed map designs, we conducted a study with 118 participants and a between group design, i.e. participants only navigated with one of the depictions. The following sections describe the study set-up in detail, focusing on the chosen test route, the participants and the interface design. Moreover, necessary annotations are described.

3.1 Test Route

The study took place in a large-scale university building. The test route was about 375 meter long and led through three different buildings (see Figure 1). The first two buildings mainly consist of open spaces such as halls or big corridors. The last part of the route was located at an office building and therefore was dominated by narrow hallways and more changes of direction. All in all, the route consisted of nine changes of direction and three floor changes. In order to identify landmarks that could be displayed in the different maps a prestudy was conducted. As a first step, decision points along the route were determined. For this purpose, potential and “real” decision points, i.e. points were a change of direction was necessary or potentially possible (see e.g. [19]) were taken into account. Moreover, at several route points spatial barriers such as doors and stairs had to be crossed. Therefore, an instruction could be necessary at these points and they were included. This resulted into 18 steps where an instruction should be provided. For every of these points a set of four landmarks was predefined according to the findings of Viaene et al. [33] and Ohm et al. [27]. This resulted in a test sample that mainly consisted of doors, stairs and furniture. Afterwards, 87 participants (44 male, 74 students, mean age = 23.12, SD = 4,46) rated the salience of every object using the questionnaire of Kattenbeck [14]. The participants were

Table 1 Identified landmarks and mean salience rating on a 5-point Likert scale (L = length of the route part in meter).

Step	Instruction	Landmark	Rating	L
1	Turn right after the stairs.	stairs	4.36	15.8
2	Turn right after the cafeteria.	cafeteria	4.16	19.1
3	Go straight ahead through the door.	door	3.44	25.9
4	Go straight ahead and pass the billboard.	billboard	4.14	24.4
5	Go straight ahead and pass the door.	door	3.74	27.1
6	Take the stairs on the right.	stairs	1.70	20.2
7	Go straight ahead and down the stairs.	stairs	3.88	25.5
8	Turn left in front of H6.	room H6	3.59	14.5
9	Go straight ahead and pass H9.	room H9	3.41	33.5
10	Turn right at the stairs.	stairs	3.96	22.8
11	Go straight ahead through the door.	door	3.67	17.3
12	Go straight ahead through the door and turn right.	door	3.31	37.8
13	Go straight ahead through the door.	door	3.63	29.9
14	Go straight ahead through the door.	door	3.86	13.1
15	Turn right and go up the stairs.	stair	4.02	6.5
16	Go through the door on the right.	door	3.34	9.5
17	Go straight ahead through the door.	door	3.77	8.5
18	Your destination is on the right.	destination	no rating	7.2

positioned at all points illustrated in Figure 1 and a map fragment showing the objects that had to be rated and the route was shown to them. As a result, the most salient object for every scene could be determined and was displayed in the map. Figure 1 also illustrates an example (step 2). Here, for instance, the cafeteria was rated as the most salient landmark (mean = 4.16 on a 5-point Likert scale) compared to the other landmarks (door mean = 3.00, billboard mean = 2.20, vending machine mean = 3,60). An overview of the chosen landmarks, their ratings and the formulated instructions is given in Table 1. Please note that at step 6 a landmark with a low rating was chosen. These stairs had to be climbed and were therefore included in the instructions. These led to wayfinding problems described in Chapter 4.

3.2 Interface Design

The prototypes were implemented in Android. The interface is subdivided into four main sections (see Figure 2). The upper right part displays a text instruction which indicates the route to take. The instructions were generated by the test designers and followed a fixed structure. They incorporated the landmark identified in the prestudy (see Section 3.1) and a simplified direction instruction, thus only referring to "left", "right" and "straight ahead" (see an overview in Table 1). In the upper left corner an arrow illustrates the direction to take, here again only showing the directions "left", "right" and "straight ahead". In addition, the landmark used to give a wayfinding instruction is displayed using an icon positioned relative to the arrow according to the current route segment. Both, the text instruction and the simplified arrow were displayed according to the recommendations of Butz et al. [5] and Kray et al. [17]. These two elements did not differ for the two test groups.

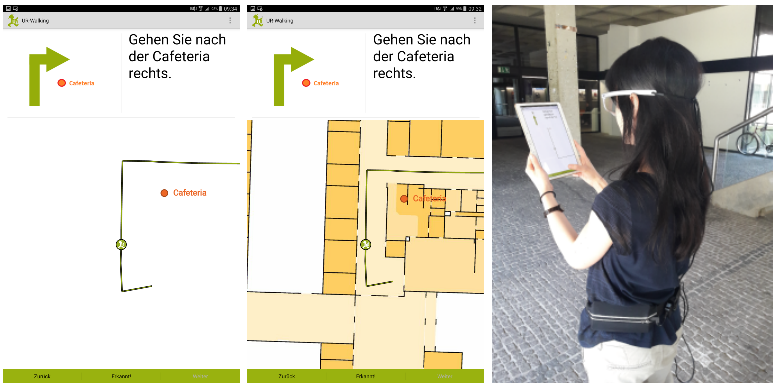

Figure 2 Interface designs (left: schematic map; middle: detailed map, right: experimental set-up). The screenshots show step 2 of the test route (see Figure 1 and Table 1). The instruction says "Go right after the cafeteria".

The main and biggest part of the screen in the middle shows the map fragment. Here, the designated current position of the user is indicated with a green manikin. The schematic map only shows the route to follow, the position of the user and the landmark, which is considered to be the minimal amount of information needed to solve a wayfinding task [32]. The detailed map is designed according to Butz et al. [5] and is a common visualisation in related studies (see e.g. [24]). Only indoor information is displayed, which means that e.g. trees and benches outdoors are not visualized. Rooms and hallways are displayed in different colours inspired by the visualisation in Schnitzler et al. [30]. Except for the landmark identified in the prestudy, no (additional) landmarks were displayed. The maps were designed for the study purpose and therefore especially for a wayfinding task. The route to follow was visualised in both map designs. The interface was "zoomable", however, the initial zoom level was fixed so that the landmarks were visible for every step. Unfortunately, no localization technique was available for this study. Therefore, the participants had to request the next navigation instruction by clicking on a "Next"-button located at the bottom right of the screen. It was possible to see previous screens using the "Back"-button (bottom left). Between these two buttons an interface element labeled "Recognized" was located. This button had to be pressed as soon as the participant had understood the instruction. By this, we wanted to record the time needed for orientation independently of the time needed for movement. This reflects the division of the navigation process in wayfinding and locomotion described by Montello [21]. The Next-button was activated only after the Recognized-button was clicked. The recognition time was considered as one of our main dependent variables.

The accuracy of the sensors used to determine the orientation of the users decreased to an insufficient level, which is a frequently reported problem in indoor ares (see e.g. [6]). Therefore, the map fragment was always oriented in direction of movement, which is preferred by users compared to north-up maps (see e.g. [31]).

3.3 Procedure and Annotation

The experiment took place in a university building during the lecture period between 10am and 16pm. The participants were picked up outside of the building and then led to the starting point of the test route. Before the experiment started they were asked to fill in the sense of direction self-assessment questionnaire of Münzer and Hölscher [23].

Figure 3 Examples of the annotation process. Left: Reference views (the boxes are labeled with "Landmark" and "Environment"). Right: Recording. Top: Gaze on a landmark referenced in the maps. Middle: Gaze on an object in the environment not referenced. Bottom: Gaze on the map element of the screen. Circular markers represent gazes.

In addition, demographic data and familiarity with smart phones and pedestrian navigation systems was collected. After this, the eye tracker was put on and calibrated using the one-point calibration. The calibration process was repeated if a gaze offset was detected. The achieved mean tracking ratio was 94.87 %. An example for the experimental set-up is shown in Figure 2. The application was started and its handling was explained using the first screen at the starting point of the route. Consequently, this step was not taken into account in the analysis. Particular focus was drawn on the explanation of the purpose of the "Recognized"-button (see Chapter 3.2), since the time measured with this interface element is one of our main dependent variables.

A between subject design was applied so that 59 participants navigated with the schematic map and 59 with the detailed map. A balanced distribution of men an women among the two prototypes was ensured.

If no more questions aroused, the test run was started. The destination was not communicated to avoid that participants could find their way without the wayfinding aid using their cognitive maps. This procedure was also applied e.g. by Münzer and Stahl [24]. The participants did not receive any additional help. If someone took a wrong turn at a decision point this was recorded as an error and the person was informed and guided back to the route. At the destination the eye tracker recording was stopped and the device was packed away. Finally, the participants had to fill in the NASA-TLX questionnaire, which measures the workload of a task (see [12]). Questions concerning the usefulness of the maps and the landmarks were asked in addition.

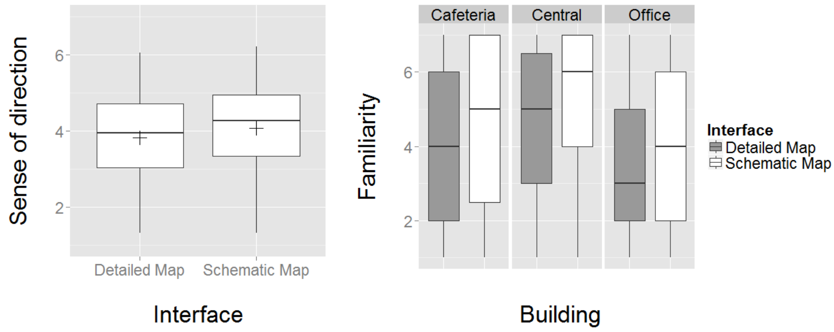

Figure 4 Sense of direction and familiarity with the test route of the participants measured with a 7-point Likert scale with higher values representing higher sense of direction respectively familiarity. The familiarity is split according to the three building of the test route.

After the experiment the eye tracking data was annotated with the help of the software of the manufacturer (SMI BeGaze 3.7). The eye tracker recording shows a video of the environment and the detected gaze (see Figure 3, right). This data was mapped on so-called reference views, which represent areas that are of interest for analysis. For this study, we annotated all gazes on the screen and distinguished the different areas "arrow", "text instruction" and "map". Moreover, we annotated gazes on the referenced landmark and other objects in the environment using "placeholder elements", i.e. labeled boxes (see Figure 3, left). Gazes only needed for locomotion, such as looking at the floor, were not considered.

3.4 Participants and Devices

The test sample consisted of 118 participants (60 male), most of them being students (110 participants). Their mean age was 23.36 years (SD = 5.00; minimum: 18 years, maximum: 54 years). Due to the eye tracker used, persons who need glasses were not allowed to participate. The subjects were very familiar with the use of smart phones (mean 5.78 on a 7-point Likert scale with higher values representing higher familiarity; SD = 1.78), but rather unfamiliar with pedestrian navigation systems (mean 3.25; SD= 1,67). Their sense of direction measured with the questionnaire of Münzer and Hölscher [23] did not differ between the two groups ($t(115) = 1{,}105$; $p = 0{,}272$; see Figure 4, left). The familiarity with the test route was distributed heterogeneously (see Figure 4, right), but did not differ amongst the two test groups taking into account the mean for all three buildings ($Z = 1.03$; $p = 0.301$).

The eye tracker used was the "SMI Eye-Tracking Glasses 2", which records gazes with a 60 Hz rate. In order to increase the accuracy of the detected gazes on the screen, the navigation prototypes were displayed on a Samsung Galaxy Tab S (screen diagonal = 26.7 cm). Other studies showed that gazes on smart phones cannot be recognized with a satisfying accuracy (see e.g. [26]).

4 Results

In the next sections the results are reported. We analyzed whether differences in wayfinding behaviour could be observed if users navigated with the schematic or the detailed map depictions. The first step was used to explain the procedure and is therefore not taken into account. In addition, the last step is not considered. Here, the instructions only referred to the destination, thus not including to a specific landmark.

4.1 Errors and Time Needed for Orientation

The experimenter took a note every time a participant took a wrong turn at a decision point. This variable is almost equally distributed among the two map versions. With each interface 10 participants had problems to find their way without additional help (see Table 2). One person made an error twice with the detailed map. Another schematic map user got lost three times. Thus, a fist insight is that wayfinding problems are not mainly caused by the map used. In fact, the situation seems to have a high impact on wayfinding performance. Especially at the beginning of the navigation process, users had problems. The initial wayfinding phase is very demanding [30], and therefore future work should address how to assist persons at this point.

The interface only displayed one landmark per step. At step 14, however, the instructions referred to tow landmarks ("Go up the stairs and through the door"). The schema was disrupted, because the two participants of the conducted prestudy with the interface stated that the steps would otherwise be too small. This led to a relatively high amount of errors, showing that only referring to one landmark could enhance navigation efficiency as described in [2].

In total the wayfinders needed 7 minutes and 46 seconds to accomplish the task. The total navigation time does not differ significantly among the two map groups ($Z = -1.58$; $p = 0.115$). However, the time needed to orient oneself determined by the Recognized-button (see Chapter 3.2) differs significantly ($Z = -2.50$; $p = 0.013$): schematic maps users have slightly lower mean values (mean schematic map = 7.23; mean detailed map = 7.39). A detailed overview for every step is depicted in Figure 5. The plot also shows – like the navigation errors already indicated – that the orientation time highly depends on the wayfinding situation and the map material only marginally influences performance. Especially the visibility of the landmark has a high impact. Due to the fact that the participants had to decide themselves when they want to see the next instruction by clicking on the Next-button, some landmarks were (not yet) visible, as some wayfinders demanded the instruction earlier than expected. For steps 6 and 10 this led to longer orientation times. An example is given in Figure 6.

4.2 Gaze Behaviour

To gain a deeper understanding how the map material was perceived, we analysed the gaze behaviour of the participants during the wayfinding task. We distinguished gazes on the three areas of the screen, i.e. the map, the arrow and the text instruction. In addition, gazes on the referenced landmarks and the environment were annotated. The results show no differences concerning the gaze duration on the environment, neither on the landmark ($Z = -0.711$; $p = 0.477$), nor the environment ($Z = -0.027$; $p = 0.979$). No differences were found concerning the arrow displayed in the upper left corner of the screen ($Z = -1.07$; $p = 0.286$). This element was hardly consulted at all (mean detailed map = 0.17 seconds; mean schematic = 0.15 seconds) and is therefore probably not necessarily needed.

Table 2 Number of participants who took a wrong turn separated by route parts. Steps that are not reported did not led to errors. Two participants got lost more than one time.

Map/Step	2	3	5	6	7	8	10	11	14	15
Schematic	1	2	1	0	1	2	1	1	3	0
Detailed	3	1	0	2	0	1	0	0	2	2

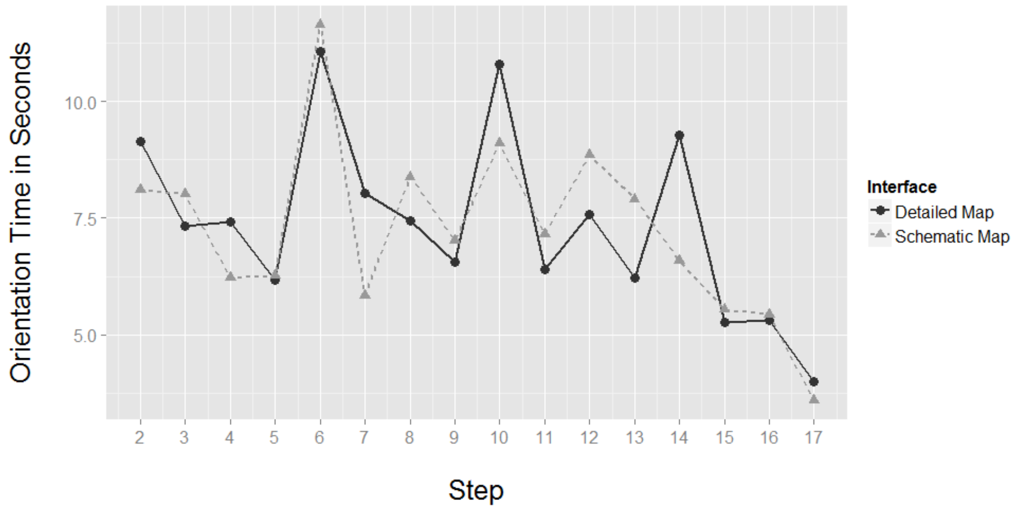

Figure 5 Time needed for orientation divided by step.

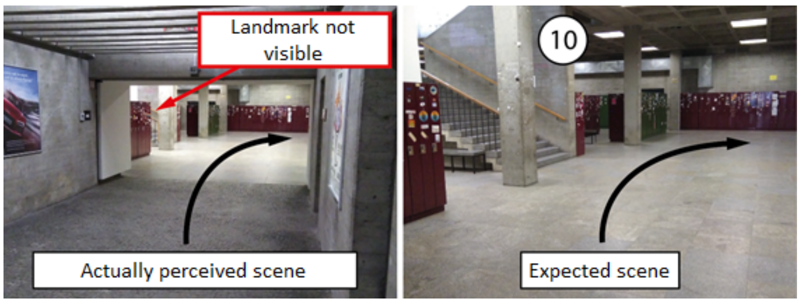

Figure 6 Bad visibility of landmark leads to longer orientation times. The example shows step 10. The instruction says "Turn right at the stairs".

However, significant differences were found for the fixation duration on the text element (t(116) = -2.24; p = 0.027; r = 0.201). Participants navigating with the detailed map looked longer at this element (mean detailed map = 1.74 seconds; mean schematic = 1.41 seconds), even though this element did not differ among the groups. Moreover, detailed map users spent significantly more visual attention on the map element (Z = -3.67; p < 0.001; r = 0.337, see Figure 7 for a detailed overview). Since this depiction contains more visual information, this was expectable. Nevertheless, the results of the orientation times show that the additional information does not lead to faster self-localisation or better performance. In fact, longer fixations on the screen seem to reflect orientation problems: the recognition time and fixation time on the map correlate significantly ($r_{sDetailed} = 0.360$; $r_{sSchematic} = 0.230$; $p_{Detailed\&Schematic} < 0.001$).

We additionally analysed the revisits on the screen. Revisits show how often users look (once again) at the interface after they looked at the environment. This is therefore a hint for disorientation and searching for additional information. This variable also revealed significant differences (Z = -6.75; p < 0.001). Wayfinders using the detailed map return more often to the map (mean detailed map = 3.74, mean schematic = 3.01).

The gazes also reflect orientation problems due to a bad visibility of landmarks. For the critical steps 6 and 10 the fixation duration on the map (see Figure 7) and the revisits

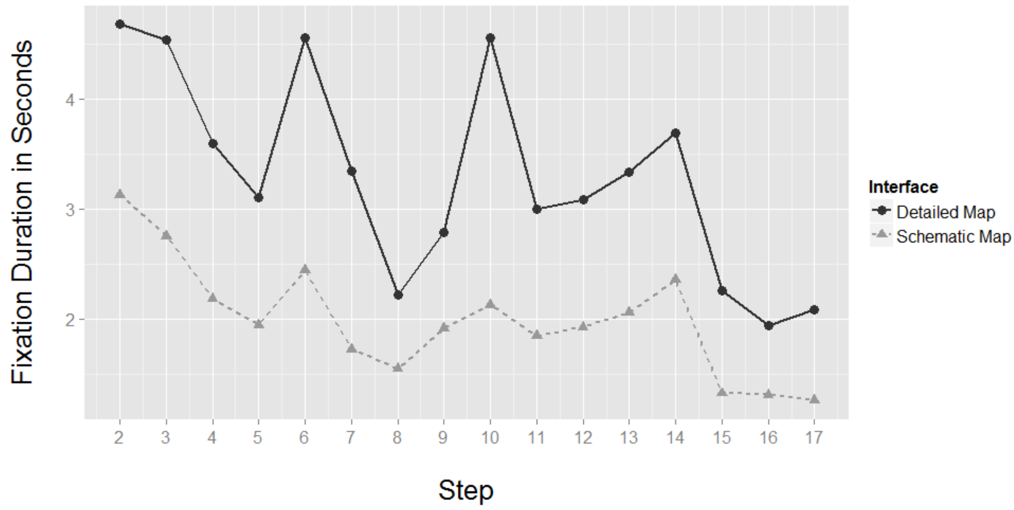

Figure 7 Fixations on the map divided by step.

are higher compared to the rest of the steps. In these situations users seem to search for information on the map in order to solve their orientation problems. Moreover, the initial orientation problems at the beginning of the route are also observable.

4.3 Questionnaire

At the end of the experiment participants were asked to fill in the NASA-TLX, which is a questionnaire often used in the context of the evaluation of pedestrian navigation systems to assess the workload of a task (see e.g. [10, 28]). Neither the overall workload ($Z = 0.238$; $p = 0.812$), nor the separate dimensions of the questionnaire differed among the two map groups ($p > 0.05$). Figure 8 shows an overview of the results. It also shows that the dimension “mental demand” was rated as the most challenging. The high amount of “outliers” at the performance dimension also show that several users stated that they were not confident with their own performance.

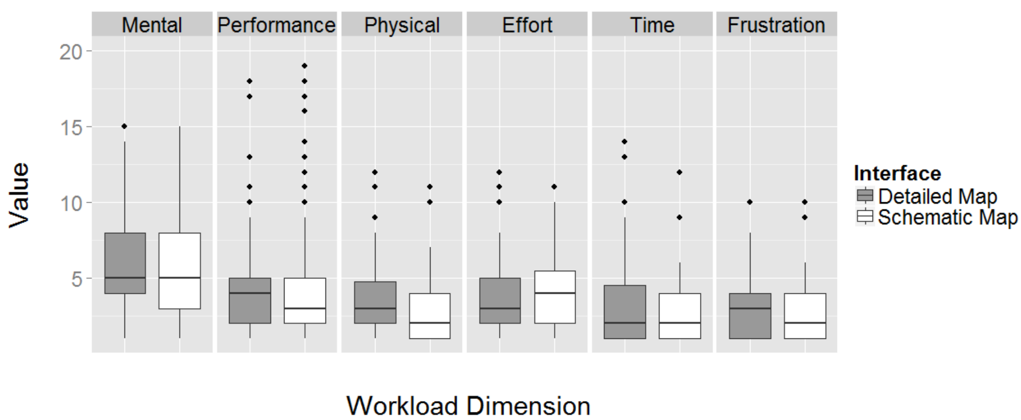

Figure 8 Workload dimensions measured with the NASA-TLX.

In addition, the wayfinders were asked to rate the helpfulness of the map depiction on a 7-point Likert scale. The ratings did not differ for the two map designs ($Z = -0.165$; $p = 0.869$) and most of the participants were very content with the visualisation (mean detailed map = 5.78, mean schematic map = 5.64). Furthermore, the participants had to rate if the chosen landmarks supported orientation. Even though several participants had observable orientation problems with some landmarks that were not always visible, the majority of the users found that the landmarks were very helpful (mean schematic map = 6.24, mean detailed map = 6.27 on a 7-point Likert scale).

5 Conclusion and Future Work

In this paper we presented a study that examined the wayfinding behaviour of pedestrians navigating with a schematic map compared to participants that additionally used a detailed map displayed on a mobile navigation system for indoor environments. In addition, both map designs depicted landmarks to support orientation. The landmarks were collected during a prestudy. The results show that wayfinders spend more visual attention on the text instruction and especially on the map material if they use the detailed map while meanwhile the orientation time slightly increases. In addition, they look more often again at the screen after they looked at the objects in the environment. The self-reported workload and satisfaction with the displayed elements did not differ for the two map designs. Wayfinders who used a schematic map did e.g. not endure higher mental demand or had to invest more effort to solve the task.

All in all, the test persons were able to solve the wayfinding task more quickly with the schematic map. Therefore, we conclude that this depiction leads to more efficient orientation and is an efficient means of displaying wayfinding information. However, the absolute differences of the time needed for orientation are very small. The detailed map is therefore still a good navigation aid. The main advantage of a schematic map is that the wayfinders have more "free" visual resources that could be used to explore the environment. Nevertheless, it is still an open question whether this map material allows the wayfinders to focus more on the environment, since we could not find any differences concerning the gazes in the real world. This question could be addressed in future work, e.g. by examining whether the users can draw more detailed sketch maps after the task. Moreover, our study clearly showed that the landmarks used to guide the pedestrians and especially their visibility have a great impact on wayfinding efficiency and interactions with the display. Therefore, the main future research direction should focus on means to adequately convey landmark information under varying conditions of the environment. If e.g. a reliable indoor localisation technique is available, the system could only refer to landmarks that are certainly visible at the current position of the wayfinder. In this context, it is also important to analyse at which decision points a map is actually needed. Most of the participants spent approximately the same amount of visual attention on the text instruction and the map. At some points during the route a text instruction could be enough to solve the wayfinding task. On the other hand, a map provides more information about the environment and could help to maintain orientation at complex decision points. Another critical situation is the initial orientation phase. In this context, displaying e.g. an overview map could help the pedestrians to gain a better understanding of the route they have to take.

Furthermore, future research should examine whether our findings are applicable for outdoor environments. In this context, e.g. Bienk et al. [3] showed that the preferred depiction depends on the sense of direction of the wayfinders, whereby persons with a "good" sense of directions benefit from more abstract depictions. In a previous study we could also show that bad-oriented users profit from detailed map material [25]. Consequently, the influence of the characteristics of the wayfinder and the navigation situations should be examined in more detail.

References

1 Gary L. Allen. Cognitive Abilities in the Service of Wayfinding: A Functional Approach. *The Professional Geographer*, 51(4):555–561, 1999.

2 Christina Bauer, Manuel Müller, and Bernd Ludwig. Indoor Pedestrian Navigation Systems: Is More Than One Landmark Needed for Efficient Self-localization? In *Proceedings of the 15th International Conference on Mobile and Ubiquitous Multimedia*, MUM '16, pages 75–79, New York, NY, USA, 2016. ACM.

3 Stefan Bienk, Markus Kattenbeck, Bernd Ludwig, Manuel Müller, and Christina Ohm. I want to view it my way: Interfaces to mobile maps should adapt to the user's orientation skills. In *Proceedings of the 12th International Conference on Mobile and Ubiquitous Multimedia*, pages 34:1–34:9, New York, NY, USA, 2013. ACM.

4 Anders Bouwer, Frank Nack, and Abdallah El Ali. Lost in Navigation: Evaluating a Mobile Map App for a Fair. In *Proceedings of the 14th ACM International Conference on Multimodal Interaction*, ICMI '12, pages 173–180, New York, NY, USA, 2012. ACM.

5 Andreas Butz, Jörg Baus, Antonio Krüger, and Marco Lohse. A Hybrid Indoor Navigation System. In *Proceedings of the 6th International Conference on Intelligent User Interfaces*, IUI '01, pages 25–32, New York, NY, USA, 2001. ACM.

6 Andreas Ettlinger, Hans-Berndt Neuner, and Thomas Burgess. Smartphone Sensor-Based Orientation Determination for Indoor-Navigation. In Georg Gartner and Haosheng Huang, editors, *Progress in Location-Based Services*, pages 49–68. Springer, Cham, 2017.

7 Conrad Franke and Jürgen Schweikart. Mental representation of landmarks on maps: Investigating cartographic visualization methods with eye tracking technology. *Spatial Cognition & Computation*, 17(1-2):20–38, 2017.

8 Christian Freksa. Spatial aspects of task-specific wayfinding maps. In *Visual and spatial reasoning in design*, pages 15–32, Sydney, 1999. Key Centre of Design Computing and Cognition, University of Sydney.

9 Georg Gartner and Verena Radoczky. About the Role of Cartographic Presentation for Wayfinding. In Emmanuel Stefanakis, Michael P. Peterson, Costas Armenakis, and Vasilis Delis, editors, *Geographic Hypermedia: Concepts and Systems*, pages 381–398, Berlin, Heidelberg, 2006. Springer.

10 Ioannis Giannopoulos. *Supporting Wayfinding Through Mobile Gaze-Based Interaction*. Dissertation, ETH-Zürich, 2016.

11 Reginald G Golledge. Human wayfinding and cognitive maps. In Reginald G Golledge, editor, *Wayfinding behavior: Cognitive mapping and other spatial processes*, pages 5–45, 1999.

12 Sandra G. Hart and Lowell E. Staveland. Development of NASA-TLX (Task Load Index): Results of Empirical and Theoretical Research. In Peter A. Hancock and Najmedin Meshkati, editors, *Human Mental Workload*, volume 52 of *Advances in Psychology*, pages 139–183. North-Holland, 1988.

13 Haosheng Huang and Georg Gartner. A Survey of Mobile Indoor Navigation Systems. In Georg Gartner and Felix Ortag, editors, *Cartography in Central and Eastern Europe: CEE 2009*, pages 305–319, Berlin, Heidelberg, 2010. Springer.

14 Markus Kattenbeck. *Empirically Measuring Salience of Objects for Use in Pedestrian Navigation.* Dissertation, Universität Regensburg, 2016.

15 Peter Kiefer, Ioannis Giannopoulos, and Martin Raubal. Where Am I? Investigating Map Matching During Self-Localization With Mobile Eye Tracking in an Urban Environment. *Transactions in GIS*, 18(5):660–686, 2014.

16 Alexander Klippel, Kai-Florian Richter, and Stefan Hansen. Wayfinding Choreme Maps. In Stéphane Bres and Robert Laurini, editors, *Proceedings of the 8th International Conference on Visual Information and Information Systems*, pages 94–108. Springer, Berlin, Heidelberg, 2006.

17 Christian Kray, Christian Elting, Katri Laakso, and Volker Coors. Presenting Route Instructions on Mobile Devices. In *Proceedings of the 8th International Conference on Intelligent User Interfaces*, IUI 03, pages 117–124, New York, NY, USA, 2003. ACM.

18 Alexandra Lorenz, Cornelia Thierbach, Nina Baur, and Thomas H. Kolbe. Map design aspects, route complexity, or social background? Factors influencing user satisfaction with indoor navigation maps. *Cartography and Geographic Information Science*, 40(3):201–209, 2013.

19 Kristin L. Lovelace, Mary Hegarty, and Daniel R. Montello. Elements of Good Route Directions in Familiar and Unfamiliar Environments. In Christian Freksa and David M. Mark, editors, *Proceedings of the International Conference on Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science*, pages 65–82, Berlin, Heidelberg, 1999. Springer.

20 David M. Mark, Christian Freksa, Stephen C. Hirtle, Robert Lloyd, and Barbara Tversky. Cognitive models of geographical space. *International Journal of Geographical Information Science*, 13(8):747–774, 1999.

21 Daniel R. Montello. Navigation. In A. Miyake and P. Shah, editors, *The Cambridge Handbook of Visuospatial Thinking*, pages 257–294. Cambridge University Press, New York, NY, US, 2005.

22 Daniel R Montello and Corina Sas. Human factors of wayfinding in navigation. In W. Karwowski, editor, *International Encyclopedia of Ergonomics and Human Factors*, pages 2003–2008. CRC Press/Taylor & Francis, London, England, 2006.

23 Stefan Münzer and Christoph Hölscher. Development and validation of a self-report measure of environmental spatial strategies. *Diagnostica*, 57(3):111–125, 2011.

24 Stefan Münzer and Christoph Stahl. Learning Routes from Visualizations for Indoor Wayfinding: Presentation Modes and Individual Differences. *Spatial Cognition & Computation*, 11(4):281–312, 2011.

25 Christina Ohm, Stefan Bienk, Markus Kattenbeck, Bernd Ludwig, and Manuel Müller. Towards interfaces of mobile pedestrian navigation systems adapted to the user's orientation skills. *Pervasive and Mobile Computing*, 26:121–134, 2016.

26 Christina Ohm, Manuel Müller, and Bernd Ludwig. Evaluating indoor pedestrian navigation interfaces using mobile eye tracking. *Spatial Cognition & Computation*, 17(1-2):89–120, 2017.

27 Christina Ohm, Manuel Müller, Bernd Ludwig, and Stefan Bienk. Where is the landmark? Eye tracking studies in large-scale indoor environments. *Proceedings of the 2nd International Workshop on Eye Tracking for Spatial Research co-located with the 8th International Conference on Geographic Information Science (GIScience 2014)*, 2014.

28 Timo Partala and Miikka Salminen. User Experience of Photorealistic Urban Pedestrian Navigation. In *Proceedings of the International Working Conference on Advanced Visual Interfaces*, pages 204–207, New York, NY, USA, 2012. ACM.

29 Arto Puikkonen, Ari-Heikki Sarjanoja, Merja Haveri, Jussi Huhtala, and Jonna Häkkilä. Towards Designing Better Maps for Indoor Navigation: Experiences from a Case Study. In *Proceedings of the 8th International Conference on Mobile and Ubiquitous Multimedia*, MUM '09, pages 16:1–16:4, New York, NY, USA, 2009. ACM.

30 Verena Schnitzler, Ioannis Giannopoulos, Christoph Hölscher, and Iva Barisic. The Interplay of Pedestrian Navigation, Wayfinding Devices, and Environmental Features in Indoor Settings. In *Proceedings of the 9th Biennial ACM Symposium on Eye Tracking Research & Applications*, ETRA '16, pages 85–93, New York, NY, USA, 2016. ACM.

31 Nanja J. J. M. Smets, Guido M. te Brake, Mark A. Neerincx, and Jasper Lindenberg. Effects of Mobile Map Orientation and Tactile Feedback on Navigation Speed and Situation Awareness. In *Proceedings of the 10th International Conference on Human Computer Interaction with Mobile Devices and Services*, MobileHCI '08, pages 73–80, New York, NY, USA, 2008. ACM.

32 Barbara Tversky and Paul U. Lee. Pictorial and Verbal Tools for Conveying Routes. In Christian Freksa and David M. Mark, editors, *Proceedings of the International Conference on Spatial Information Theory. Cognitive and Computational Foundations of Geographic Information Science*, pages 51–64, Berlin, Heidelberg, 1999. Springer.

33 P. Viaene, A. Vanclooster, K. Ooms, and P. De Maeyer. Thinking aloud in search of landmark characteristics in an indoor environment. In *Ubiquitous Positioning Indoor Navigation and Location Based Service (UPINLBS)*, pages 103–110, 2014.

34 Dirk Wenig, Alexander Steenbergen, Johannes Schöning, Brent Hecht, and Rainer Malaka. ScrollingHome: Bringing Image-based Indoor Navigation to Smartwatches. In *Proceedings of the 18th International Conference on Human-Computer Interaction with Mobile Devices and Services*, MobileHCI '16, pages 400–406, New York, NY, USA, 2016. ACM.

35 Jan M. Wiener, Simon J. Büchner, and Christoph Hölscher. Taxonomy of Human Wayfinding Tasks: A Knowledge-Based Approach. *Spatial Cognition & Computation*, 9(2):152–165, 2009.