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Landmark-Based Navigation Instructions Improve Incidental Spatial Knowledge Acquisition in Real-World Environments

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Abstract**.** The repeated use of navigation assistance systems leads to decreased processing of the environment. Previous studies demonstrated that auditory references to landmarks in navigation instructions can improve incidental spatial knowledge acquisition when driving a single route through an unfamiliar virtual environment. Based on these results, three experiments were conducted to investigate the generalizability and ecological validity of incidental landmark and route knowledge acquisition induced by landmark-based navigation instructions.

In the first experiment, spatial knowledge acquisition was tested after watching an interactive video showing the navigation of a real-world urban route. A second experiment investigated incidental spatial knowledge acquisition during assisted navigation when participants walked through the same real-world, urban environment. The third experiment tested the acquired spatial knowledge two weeks after participants had walked through the real-world environment.

All experiments demonstrated better performance in a cued-recall task for participants navigating with landmark-based navigation instructions as compared to standard instructions. Different levels of information provided with landmark-based instructions impacted landmark recognition dependent on the delay between navigation and test. The results replicated an improved landmark and route knowledge when using landmark-based navigation instructions emphasizing that auditory landmark augmentation enhances incidental spatial knowledge acquisition, and that this enhancement can be generalized to real-life settings.

This research is paving the way for navigation assistants that, instead of impairing spatial knowledge acquisition, incidentally foster the acquisition of landmark and route knowledge during every-day navigation.

Keywords: automation, spatial knowledge acquisition, real-world, cued-recall

1 Introduction

1.1 Background

Navigation aids have become common everyday tools (Axon et al., 2012; Kalin & Frith, 2016; Kitchin & Dodge, 2007). They provide visual as well as auditory guidance as a support during wayfinding through known and unknown environments (Allen, 1999). With the use of navigation aids, wayfinding evolved from analog 2D map-based tasks into digitally assisted instruction following tasks.

Several studies investigated the users' interaction with navigation aids in order to describe and understand the underlying cognitive processes. One finding was that the use of automated assistance systems was associated with divided attention between the movement related task and the assisted navigation (Fenech et al., 2010; Gardony et al., 2013, 2015). This resource allocation conflict increases the reliance on the navigation assistance in order to reduce attentional demands (Baus et al., 2001; Klippel et al., 2010; Parush et al., 2007) leading to an automation bias (Lin et al., 2017). The users tend to hand over the decision-making to the automated system (Bakdash et al., 2008; Fenech et al., 2010; Parush et al., 2007). They follow the system instructions without checking other available information (Mosier et al., 1996; Parasuraman, 2000) and this over-reliance leads to a decrease in the processing of the surrounding environment (Fenech et al., 2010; Hirtle & Raubal, 2013; Leshed et al., 2008).

As a consequence, when the navigation aid is no longer reliably functioning (e.g., because of system errors or GPS signal loss), people are more likely to get lost because of their inability to extract navigation relevant information from the environment and to orient using their own sense of direction. However, even when the system works properly, the risk of getting lost remains based on inadequate application of or over-reliance on the navigation assistance system. This was revealed in a corpus of 158 so-called "Death by GPS" incidents published in the English news between 2010 and 2017 (Lin et al., 2017). Only those reports were chosen that contained incidents caused by an improper use of navigation assistance systems reporting an unusually high number of single-car crashes (32%) and that most of the "Death by GPS" incidents happened in an unknown environment (78%). These data point to a relative increase of rare accidents involving no other road users demonstrating that the use of automated assisting technologies can negatively impact the primary driving task.

Thus, the first goal of an improved navigation assistance system should be to maintain the ability to extract navigation relevant information from the environment without endangering the users' safety. One solution to this end is the inclusion of environmental information about salient objects, so called landmarks (Evans et al., 1982), in the navigation instructions (Goodman et al., 2005; Li et al., 2014; A. May et al., 2001). It was shown that landmark knowledge can be incidentally acquired during navigation to a similar level as intentional learning (Chrastil & Warren, 2012; Van Asselen et al., 2006). Compared to visual augmentation methods, acoustic navigation instructions have the advantage to not interfere with visual attention necessary to observe the ongoing traffic (May & Ross, 2006; Ross et al., 2004). Ross and colleagues investigated landmark-based auditory navigation instructions regarding their usability for pedestrians. The authors demonstrated the effectiveness of landmark-based auditory instructions leading to fewer navigation errors and increased navigator's confidence during navigation, as compared to a control group. While the study by Ross and colleagues demonstrated improved navigation performance, the authors did not test for the impact of auditory landmark information on spatial knowledge acquisition.

To test whether auditory landmark-based navigation instructions lead to increased processing of environmental information beyond improving safe navigation, Gramann and colleagues (2017) referenced landmarks at intersections in a virtual driving task. Landmark augmentation was implemented by naming landmarks and providing additional information about the landmark at intersections with route direction changes. This resulted in incidental acquisition of navigation relevant information about the environment (Gramann et al., 2017). The improved landmark and route knowledge acquisition with landmark-based navigation instructions was observable even when tested three weeks after a single exposure to an unfamiliar environment (Wunderlich & Gramann, 2018). It was further found to be associated with changes in brain activity likely reflecting increased information recollection during cued-recall of landmark- and route-knowledge about the navigated environment in general (Wunderlich & Gramann, 2018).

The results of both virtual driving studies in Gramann and colleagues (2017) as well as Wunderlich and Gramann (2018), showed a significantly improved recognition performance for landmarks at intersections with route direction changes when navigators received landmark-based instructions (e.g., "At the zoo, turn left. There you can visit various animals") as compared to standard navigation instructions known from commercial systems (e.g., "At the next intersection turn left.") These results support the assumption that the inclusion of landmark information in navigation instructions was associated with directing the users' attention towards environmental features. Landmarks (i.e., salient and lasting aspects of the surrounding environment like buildings) are essential elements of spatial representations and necessary for conceiving spatial relations (Ekstrom & Isham, 2017; Siegel & White, 1975). Referencing landmarks in auditory navigation instructions might thus be a promising way to foster processing of the environment that in turn leads to incidental spatial knowledge acquisition during the use of navigation assistance systems. Importantly, the enhanced processing of the environment when using landmark-based instructions did not impact the subjective mental load or the driving behavior, thus, securing safety of the primary driving task (Gramann et al., 2017; Wunderlich & Gramann, 2018).

The reported studies by Gramann and colleagues (2017) as well as Wunderlich and Gramann (2018) used two versions of landmark-based navigation instructions that included the name of a landmark located at the intersection to guide attention to the surroundings and additional landmark information to foster more elaborate processing of the environment which can be linked to lasting memory traces (Lockhart and Craik, 1990). To this end, one instruction condition added personally relevant information to landmarks (for example: "Turn right at the bookstore. There, you can buy books of J.R.R. Tolkien." in case J.R.R. Tolkien was the favorite author of the tested participant). Personal interests in different categories were acquired prior to the experiment and navigation instructions were individualized for each participant accordingly. A second instruction condition provided redundant information of comparable length as the personal-reference condition and was identical for all participants in this group (e.g., “Turn right at the bookstore. There, you can buy books.”) The use of these landmark-based navigation instructions enhanced spatial knowledge compared to standard navigation instructions, whereby the personal-reference did not differ significantly from the redundant version.

1.2 The current study

The present study aimed at extending the results reported in earlier studies using landmark-based navigation instructions (Gramann et al., 2017; Wunderlich & Gramann, 2018). More specifically, we investigated whether the improved incidental spatial knowledge acquisition that was observed for driving simulations would generalize to more ecologically valid scenarios. The previous experiments took place in a driving simulator setup (Gramann et al., 2017; Wunderlich & Gramann, 2018) that lacked naturalistic self-motion cues, other traffic participants, and natural visual information. To investigate whether incidental spatial knowledge acquisition with landmark-based navigation instructions can be observed also for real-world scenarios, we conducted three experiments.

In Experiment 1, we transferred the navigation paradigm to a pedestrian context using real-world visuals including other traffic participants and a real built environment. An interactive video was created showing a pedestrian’s first-person perspective while navigating through Berlin, Germany. The video was a realistic representation of city navigation while allowing control of stimulus material for all participants. A replication of the positive impact of landmark-based instructions in this setup would emphasize the generalizability from driving simulations to pedestrian navigation. While participants in both driving simulations and video navigation are seated, the latter condition comprises realistic landmarks which might be less salient compared to the surrounding buildings and it contains a complex dynamic environment with many other agents attracting attention.

Experiment 2 and 3 investigated incidental spatial knowledge acquisition during real-world assisted pedestrian navigation through the city of Berlin. Experiment 2 investigated the identical route and stimuli that were used in Experiment 1 (Wunderlich & Gramann, 2020). The replication of the spatial learning advantage of landmark-based navigation instructions in the real world with unrestricted movement would warrant its ecological validity despite the additional impact of naturalistic self-motion cues and a less controlled setup varying according to the behavior of other agents and weather conditions.

Experiment 3 extended the route used in Experiments 1 and 2 to increase the number of intersections. In addition, the last experiment introduced a break of two weeks between the navigation phase and the subsequent spatial tests similar to (Wunderlich & Gramann, 2018). The paradigm extensions enabled investigating landmark-based instructions using a long route through a complex real environment and testing the incidental spatial knowledge after a longer period of time allowing for interfering walks.

Besides approaching ecological validity, we advanced the auditory landmark-based navigation instructions used to trigger processing of the environment. As the reference to personal interests did not significantly contribute to incidentally acquired spatial knowledge beyond the landmark reference in the previous studies, we moved away from individualized navigation instructions to a more applicable one-for-all approach. To foster a more elaborate processing of the environment during assisted navigation the presented studies used a long navigation instruction condition that named landmarks and provided additional semantic information about the landmark (e.g., “Turn right at the bookstore. There, public readings take place every week.”) Because previous studies revealed improved spatial knowledge acquisition for any landmark-based navigation instructions, we also introduced a short navigation instruction condition to test whether simply referencing a landmark without additional information might already foster spatial knowledge acquisition (e.g. “Turn right at the bookstore.”) This condition was similar to the landmark-based navigation instructions in the usability study by Ross and colleagues (2004). In summary, in three experiments, both short and/or long landmark-based navigation instructions were compared with a control group that received standard auditory navigation instructions as known from commercial navigation aids referring to the next intersection (e.g. “Now, turn right.”).

We expected to replicate a positive impact of landmark-based navigation instructions on processing of the environment and thus incidentally acquired landmark and route knowledge in both the controlled video scenario as well as the real-world setting. Similar to previous studies, better performance in the cued-recall task following the assisted navigation was chosen as indicator for advanced landmark and route knowledge. Furthermore, we expected that participants receiving long navigation instructions outperform those receiving short navigation instructions. Finally, we hypothesized that landmark-based navigation instructions lead to a generally increased processing of the environment (also during straight segments) rather than only intersections that were associated with navigation instructions.

In all three experiments reported here, different participants were recruited that were naïve to the route and had no prior knowledge of the tasks. Physiological data were recorded but will not be reported here since the focus of the present report is on the comparison of performance in three different experiments investigating ecological validity. The results from the physiological data analyses have been or will be reported elsewhere.

2 Experiment 1

The aim of Experiment 1 was to test landmark-based navigation instructions in a more realistic environment providing real-world visuals. To this end, an interactive video was created showing a pedestrians' first-person perspective during real-world navigation through the city of Berlin as an example for an urban environment.

2.1 Material and methods

2.1.1 Participants

Power analysis (GPower 3.1.9.4) was based on the large effect size (η_p^2 = .2, which equals f = 0.5, and correlation among repeated measures = .5) found by a similar analysis in the previous data (Gramann et al., 2017). The projected sample size when comparing three groups in a repeated-measures (two-levels) ANOVA targeting the between-factor effect and ensuring alpha = .05 and power = .80 was N = 33 (eleven per group).

The data of forty-three participants, assigned to three different navigation instruction groups, was evaluated in this experiment. All participants had normal or corrected to normal vision and gave written informed consent prior to the study. The study was approved by the local ethics committee. The sample included 22 women and gender was balanced across navigation instruction conditions (14 participants in standard, 7 females; 14 in short, 7 females; and 15 in the long instruction condition, 8 females). The age ranged from 19 to 34 years (M = 26.2 years, SD = 2.75 years). Participants were recruited through an existing database or personal contact and were reimbursed monetarily or received course credit. All participants were naïve to the tasks and did not participate in any of the other experiments. To assure that participants were unfamiliar with the route, we used an online questionnaire prior to the experiment. Participants were asked to rank up to five metro stations of Berlin according to their frequency of personal use. If one of the stations was close to the route, the participant was excluded from the experiment. After the navigation task, the participants were asked to rate their familiarity with the navigated route on a scale ranging from 0% (completely unknown) to 100% (completely known) and if their response exceeded 50% familiarity they were excluded from analyses before they proceeded with the spatial tasks. The reported sample had an averaged familiarity score of M = 9.88% (SD = 11.1%, standard: M = 9.43%, SE = 3.05%, short: M = 10.0%, SE = 3.05%, long: M = 10.2%, SE = 2.95%, $F(2,40)$ = 0.018, p = .983, η_p^2 = .001).

2.1.2 Procedure

Following previous experimental protocols (Gramann et al., 2017; Wunderlich & Gramann, 2018), the experiments consisted of two parts. The first part was an assisted navigation phase in which participants followed auditory navigation instructions to navigate along a predefined route. In the second part, participants had to solve different tasks testing their spatial knowledge about the navigated environment. Participants were not informed prior to the second part that they would be tested on the navigated environment. The entire experiment took place in a controlled laboratory environment (Figure 1a) and lasted 2 hours and 40 minutes. Participants were seated in front of a display and interacted with the video scenario by using the keyboard in front of them. They were equipped with electroencephalography (EEG; BrainAmps, Brain Products, Gilching, Germany) and eye movements were recorded with a desktop-based eye-tracker (SMI RED 5, SensoMotoric Instruments, Teltow, Germany).

Figure 1: ***Experimental setup of Experiment 1***
1a) Interactive video setup of Experiment 1. The screen in front of the participant displayed the video and was equipped with the eye-tracker,a second screen was used to check the raw EEG-data, and the laptop for eye-tracking data collection. b) Video snapshot of a landmark at an intersection ("public restroom") as seen during video-based navigation as well as used in the cued-recall task (pictures were presented in color).

2.1.3 Navigation phase

In the previous studies, landmarks at intersections with a change in route direction were labelled navigation relevant while landmarks at intersections without direction change and no instruction were labelled navigation irrelevant. For Experiment 1 and all following experiments, this definition was adapted to the pedestrian context that provided more time between intersections as compared to simulated driving. Participants received auditory navigation instructions prior to each intersection. Thus, landmarks located at *intersections* were considered as one category irrespective of whether the route remained straight or turned left or right. Landmarks located along *straight segments* between intersections constituted the second landmark category. Both types of landmarks at intersections and along the route can be perceived as navigation relevant. While landmarks at intersections can be associated with changes in route direction, it was shown for pedestrian navigation assistance that landmarks located along straight route segments allow for confirming correct route progress and improve user confidence during navigation (May et al., 2003; Rousell & Zipf, 2017). However, the present experiments provided landmark-based instructions only for landmarks at intersections. Landmarks in between intersections were not accompanied by navigation instructions.

Participants watched a video showing real world recordings complemented by auditory navigation instructions. The video content for the navigation task was recorded with a GoPro Hero 4 (GoPro. Inc., San Mateo, USA) from a pedestrians' perspective (see Figure 1b). The camera person was continuously recording while walking a predefined route. During the video, various other road users were visible. Removing the real-world audio allowed for high realism of the visuals without considering other auditory stimuli than the auditory navigation instructions. The video was accelerated by 1.1 times the original speed to shorten the navigation task to approximately 35 minutes without distorting the navigation experience. The displayed route through Charlottenburg, Berlin in Germany, was 3.7 km long and passed twenty intersections containing 14 route direction changes. The stimulus material was identical for all participants and only the navigation instructions differed between the groups. Besides the standard navigation instructions, the short and long landmark-based navigation instructions were tested.

Auditory navigation instructions were presented via loudspeakers prior to each intersection. When arriving at an intersection, the video stopped and a participants' response according to the instructed direction was required. Participants indicated the navigation directions using the left (turn left), up (go straight), or right (turn right) arrow key. The video did not commence without a response. This interaction was implemented to ensure the participants' attention to the instructions and the route. Irrespective of whether the response was correct or not, pressing one of the response keys started the video again.

After the video navigation phase, the subjectively experienced mental load was measured using the NASA-TLX (Hart, 2006; Hart & Staveland, 1988). In addition, participants answered questions about route familiarity and acceptance of the modified navigation instructions.

2.1.4 Test phase

The test phase followed the navigation phase after a short break (as in Gramann et al., 2017). This second part consisted of sketch map drawing, a cued-recall task, the Perspective Taking/Spatial Orientation Task (PTSOT; Hegarty & Waller, 2004), and the circle task (triangular pointing task). Questionnaire data about demographic characteristics, individual navigation and learning habits, as well as spatial abilities were collected at the end of the experiment. The self-reported sense of direction was rated using 7 point Likert scale for agreement with the key item "My sense of direction is very good" (SOD; Hegarty et al., 2002; Kozlowski & Bryant, 1977).

Only the cued-recall task is reported in detail here as it was the only task that was used in all three experiments as well as in the previous studies. This way, five studies could be directly compared, and the results allowed for conclusions about the generalizability of the impact of landmark-based navigation instructions for different navigation contexts.

2.1.5 Cued-recall task

The cued-recall task combined a simple landmark recognition with a route direction response comparable to Huang and colleagues (2012). The task of the participant was to correctly recognize pictures taken from the navigated environment as being part or not being part of the previously navigated route. In case of recognizing a landmark, participants were instructed to respond according to the respective route direction at this landmark location (straight, left, right). To capture the overall acquired landmark and route knowledge, we used three landmark types which were categorized according to their location: a) landmarks at *intersections* that were referenced in the modified navigation instructions, b) landmarks located at *straight segments* along the route, and c) *novel* landmarks that were part of the environment but had not been encountered during the navigation phase (e.g., buildings in a parallel street). There were no navigation instructions during straight segments and thus respective landmarks were not referenced during navigation. Landmarks at intersections and landmarks along straight segments of the previously navigated route should be indicated as known landmarks by responding with the respective direction in which the route had continued during assisted navigation while novel landmarks (independent of location) should be identified as unknown. Half of the novel landmarks were located at intersections while the other half was located alongside straight segments of a street that provided no turning opportunities.

We analyzed response rates for known and novel landmarks at intersections as well as at straight segments of the route using signal detection theory to compute the sensitivity measure d' (Atkinson, 1963; Marcum, 1960). This measure allowed better control for possible response biases as discussed in Wunderlich and Gramann (2018) by considering the false alarm rate for novel landmarks. Comparing the sensitivity across navigation instruction conditions allowed for investigating differences in the acquired landmark knowledge. To investigate the incidentally acquired route knowledge, the performance in a cued-recall task was analyzed as a second dependent measure using the percentage of correct direction responses regarding the landmarks at intersections. This measure represents a combination of landmark and route knowledge of the navigated environment because correct responses required associative memory of the respective route direction. A higher percentage of correct responses represents better route knowledge that can be recollected based on the presented picture cues.

In the cued-recall task of Experiment 1, twenty pictures of each landmark type (intersections, straight segments, novel) were randomized and presented one by one on a desktop screen. Pictures of intersections and straight segments were screenshot from the navigation video. Screenshots from additional video material which was taken the same day as the navigation video served as novel landmarks. All landmarks were presented from the pedestrians' point of view including their immediate surroundings (see Figure 1b). Each landmark was displayed for 3 seconds and then replaced by four arrow keys indicating the response options. Participants were instructed to press the right/left arrow key, in case the route had turned right/left at the displayed landmark, respectively. In case the route had proceeded straight ahead, irrespective whether at intersections or at straight segments, the required response was to press the up-arrow key. In case the landmark had not been encountered previously, participants were asked to press the down-arrow key. The location of landmarks relative to the intersections (left, right, before or after the intersection) did not provide any indication for the respective turning directions. Following each response, participants were asked how confident they were about their given answer on a six-point scale ranging from "1 - very sure" to "6 - I did not know" and a seventh option to state "I know that my last response was wrong".

2.1.6 Statistical analysis

Statistical analysis was performed using the statistics software SPSS (International Business Machines Corporation (IBM) Analytics, Armonk, USA).

To control for an impact of individual differences on the dependent variables, the percentage of correct responses to each landmark type and sensitivity values were correlated with the self-reported SOD and the averaged error in the PTSOT to test for a covariance of performance and subjective or objective spatial abilities, respectively. The same way, we also tested a potential influence of subjective mental load during the navigation task. In case of significant correlations with performance in the cued-recall test, the measures were used as covariate in the respective analysis.

The mixed-measure analysis of variance (ANOVA; ANCOVA in case of significant correlations with the additional measures) testing the incidentally acquired landmark knowledge used the between-subject factor navigation instruction condition (*standard, short, long*) and two levels for the factor landmark type (*intersections, straight segments*). The first, *intersections*, counted all responses as a hit that correctly indicated that the landmark was encountered during navigation. This response represents the recognition sensitivity for intersection landmarks. The second, *straight segments*, represented the sensitivity to the landmarks along the route.

Incidentally acquired route knowledge was tested using an ANOVA (ANCOVA in case of significant correlations with the additional measures) for the percentage of correct responses to landmarks at intersections. The between-subject factor was navigation instruction (*standard, short, long*). Likewise, the overall rating of confidence when responding to the landmark cues was tested using an ANOVA comparing the navigation instruction conditions.

Post-hoc comparisons were computed comparing the instruction conditions and p-values were corrected for multiple comparisons using Bonferroni. As an indicator of effect size, partial eta squared was calculated.

2.2 Results

2.2.1 Individual measures

Individual measures of the PTSOT revealed a mean score of $M = 26.7°$ ($SD = 22.9°$) with comparable group means for the three navigation instruction groups (standard: $M = 23.2°$, $SE = 6.22°$, short: $M = 29.1°$, $SE = 6.22°$, long: $M = 27.5°$, $SE = 6.01°$, $F(2,40) = 0.24$,

p = .787, η_p^2= .012). Similarly, the SOD rating was comparable across navigation instruction conditions with and overall mean of M = 3.88 (*SD* = 1.56) and comparable group means (standard: *M* = 3.93, *SE* = 0.42, short: *M* = 3.43, *SE* = 0.42, long: *M* = 4.27, *SE* = 0.40, $F(2,40)$ = 1.05, p = .358, η_p^2 = .050). The subjective mental load during assisted navigation rated on a scale from 1 (low) to 100 (high) with an overall mean of *M* = 21.2 (*SD* = 18.0) and no differences between the navigation instruction groups (standard: *M* = 21.4, *SE* = 4.80, short: *M* = 16.2, *SE* = 4.80, long: *M* = 25.7, *SE* = 4.64, $F(2,40)$ = 1.00, p = .375, η_p^2 = .048).

The Spearman correlation of the SOD rating with the dependent variables was significant for d' of landmarks at intersections (ρ = .423, *p* = .005, all other $|\rho|$'s < .193, p's > .217). The averaged error of the PTSOT correlated negatively with d' for both, landmarks at intersections (ρ = -.307, *p* = .046) and those at straight segments (ρ = -.312, *p* = .042), the correlation with percentage correct responses to landmarks at intersections was not significant (ρ = -.100, *p* = .523). Subjective and objective measures of spatial ability correlated positively with performance in the cued-recall task. Subjective mental load did not correlate with any of the dependent measures (all ρ's < .210, p's > .177). The mean error of the PTSOT was included as a covariate in the 2x3 ANOVA testing the recognition sensitivity of the participants due to its significant correlation with both factor levels.

2.2.2 Landmark knowledge

The recognition sensitivity for landmarks at intersections had an overall mean of *M* = 1.17 (*SD* = 1.06) and divided for navigation instruction groups (standard: *M* = 0.98, *SD* = 1.17, short: *M* = 0.81, *SD* = 0.88, long: *M* = 1.69, *SE* = 0.97). Recognition sensitivity for landmarks at straight segments reached an overall mean of *M* = 1.23 (*SD* = 0.98) and each navigation instruction group (standard: *M* = 1.53, *SD* = 0.87, short: *M* = 0.94, *SD* = 1.19, long: *M* = 1.22, *SE* = 0.83). All values can be seen as group-boxplots and individual measures in Figure 2. The results of the ANCOVA testing recognition sensitivity with the PTSOT error as covariate revealed a significant main effect of the covariate ($F(1,39)$ = 8.37, p = .006, η_p^2 = .177). The interaction of landmark type and navigation instruction condition did not reach significance ($F(2,39)$ = 2.51, p = .095, η_p^2 = .114). The main effects of navigation instruction condition and landmark type and their interaction with the covariate PTSOT were also not significant (all p's > .137).

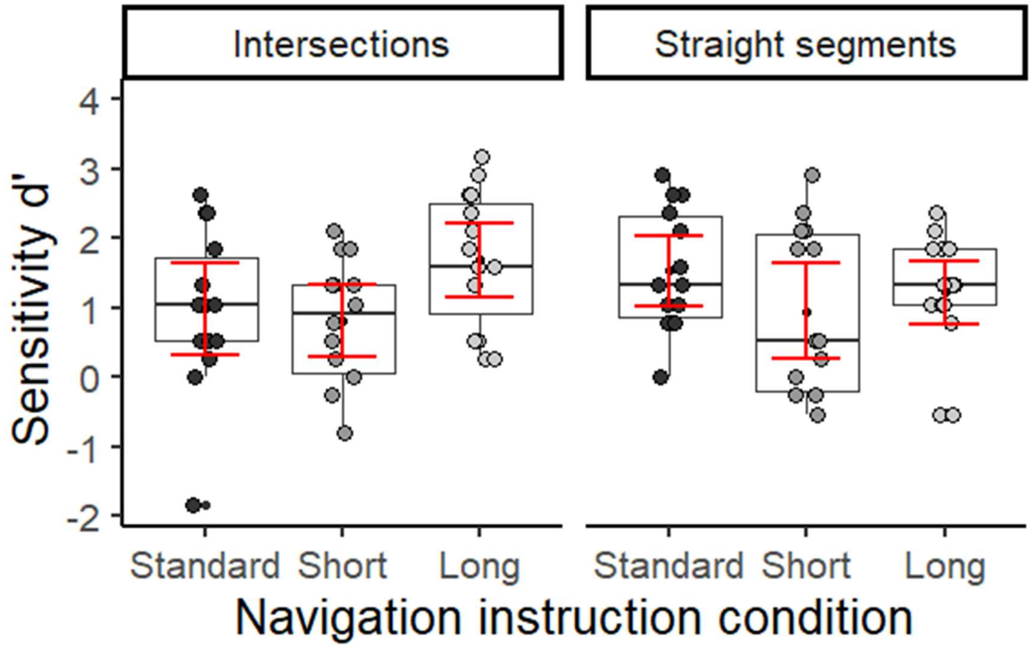

Figure 2: ***Recognition sensitivity in Experiment 1***

The recognition sensitivity for correctly recognizing familiar landmarks presented as box plots with single subject values of d' and red error bars representing the 95% CI of the mean. d' equals the z-standardized false alarm rate subtracted from the z-standardized hit rate. The left column displays recognition sensitivity for landmarks at intersections and the right column displays recognition sensitivity for landmarks at straight segments.

2.2.3 Route knowledge

Figure 3 displays group and individual route response performance for nineteen of the twenty landmarks at intersections. One navigation instruction for the short navigation instruction was presented incorrectly during video-based navigation. Thus, the respective landmark cue was removed from the analysis of the route knowledge for all navigation instruction conditions. An ANOVA testing the percentage correct responses regarding landmarks at intersections revealed a significant effect of navigation instruction condition ($F(2,40) = 6.43$, $p = .004$, $\eta_p^2 = .243$). Post-hoc comparisons revealed that the performance in the long navigation instruction condition was better (*M* = 65.3%, *SE* = 3.47%) than in the standard instruction condition (*M* = 47.7%, *SE* = 3.59%, *p* = .003, 95% CI [5.57 29.5]). The short navigation instruction condition revealed intermediate performance (*M* = 55.3%, *SE* = 3.59%, *p*'s > .113).

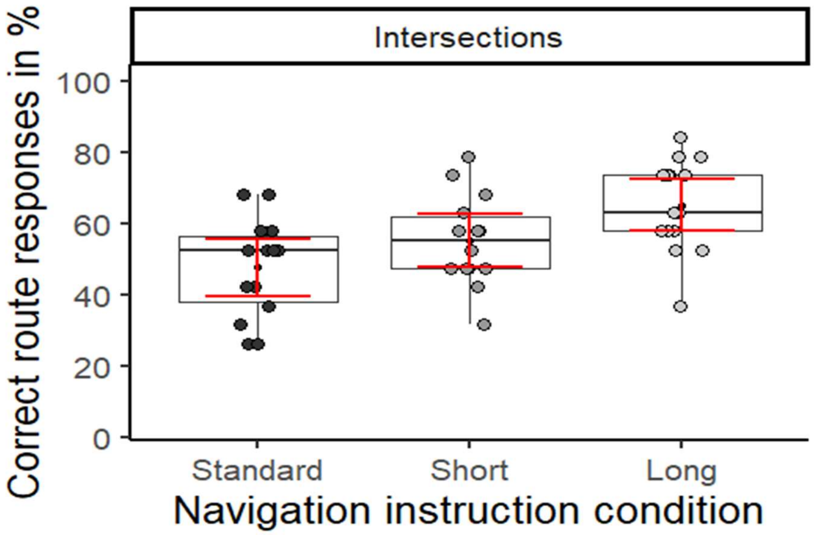

Figure 3: ***Acquired route knowledge in Experiment 1***

Boxplots and single subject performance scores represent the percentage of correctly indicated route direction after presentation of landmarks located at intersections during the cued-recall task. Red error bars depict the 95% CI of the mean. The performance measure could reach nine-teen different values with 100% when responses to all nine-teen landmarks at intersections were correct.

2.2.4 Confidence Ratings

Participants rated their confidence on a six-point scale ranging from "1 - very sure" to "6 - I did not know" with an overall mean of *M* = 2.30 (*SD* = 0.54). Navigation instruction groups did not differ significantly (standard: *M* = 2.39, *SD* = 0.57, short: *M* = 2.38, *SD* = 0.61, long: *M* = 2.16, *SD* = 0.44, $F(2,40)$ = 0.80, *p* = .455, η_p^2 = .039).

2.3 Discussion

In Experiment 1, a paradigm shift from simulated driving to video-based pedestrian navigation was realized. This allowed us to test the effect of landmark-based navigation instructions on incidental spatial knowledge acquisition in a more realistic environment than simulated driving while allowing participants to remain seated as in the driving simulator study by Gramann and colleagues (2017). Two different landmark-based navigation instructions (short and long) were compared with a control group that received standard navigation instructions.

Participants in the different navigation instruction groups revealed common and comparable spatial abilities as assessed with the PTSOT and the SOD and better performance in the spatial tasks was linked to subjective and objective assessment of spatial abilities rendering the task sensitive to spatial abilities.

The incidentally acquired landmark knowledge was tested comparing the recognition sensitivity measure between the navigation instruction conditions and landmark types. Recognition sensitivity for landmarks at intersections and straight segments was low but above chance level for all navigation instruction conditions. There was no significant main effect of the navigation instruction condition when the influence of the covariate perspective taking was controlled for. Together with the non-significant interaction with the factor landmark type the results did not replicate previous findings of a positive impact of landmark-based navigation instructions on landmark knowledge. The failure to replicate previous results might be explained by the rather passive state of participants during video navigation that required only watching movement through space with short responses at intersections. This seemed to have diminished the attention allocation effects provoked by different auditory navigation instructions demonstrated in earlier studies. As the video did not require any control of a primary task and walking speed was relatively slow, participants were able to fully concentrate on the instructions and the environment. Possibly, differences in incidental spatial knowledge acquisition become only noticeable in actual dual-task conditions with the primary task (e.g., driving or real walking) requiring attentional resources. Furthermore, the task was interrupted at each intersection by presenting the figure with the three response keys. Stopping and masking the video content might have artificially prevented the processing of the environment during intersection phases of the video navigation.

The results of incidentally acquired route knowledge with on average 56% correct direction responses and three possible response options were moderate and revealed a positive impact of more detailed landmark-based navigation instructions. The long instructions condition outperformed the control group and tended to be better than the short version of the landmark-based instructions. This replicates the previous results of Gramann and colleagues (2017) and Wunderlich and Gramann (2018) even though new modifications of landmark-based navigation instructions were introduced. In addition, the navigation context had changed from simulated driving to a video of pedestrian navigation that showed real-world visuals and included other traffic participants. Confidence ratings after direction responses were fairly confident and did not differ between navigation instruction conditions.

However, the new video-based setup was influenced by the individual perspective taking ability. The covariation with the PTSOT results might be due to the rather passive, video-based setup that allowed participants to process their surrounding environment with significantly more time as compared to simulated driving. At each turn, the video perspective changed whereas the physical reference frame of the navigator remained the same. Thus, individual differences in spatial abilities, like perspective taking or to some extent also the self-reported sense of direction, might have had a stronger influence on spatial knowledge acquisition during video watching. This needs to be considered when drawing conclusions about reliability and generalizability of the effects.

This first experiment replicated some of the results from previous studies but still lacked natural movement and the accompanying kinesthetic and proprioceptive information during real pedestrian navigation that might further support spatial knowledge acquisition of the surroundings. To allow for multimodal information integration of all senses involved in natural navigation through the real world, Experiment 2 implemented a real-world navigation task with pedestrians actively navigating the same route through Berlin that was shown in the video in the first experiment.

3 Experiment 2

In the second experiment, the experimental protocol changed from a stationary laboratory setup to a real-world setting allowing for free movement of navigators through their environment. This modification aimed at testing the ecological validity of the previously demonstrated incidental spatial learning effect during the use of long landmark-based navigation instructions in an unrestricted, real-world setting. The analysis of the brain activity accompanying assisted navigation in the real world was reported in a separate manuscript (Wunderlich & Gramann, 2020).

3.1 Material and methods

3.1.1 Participants

The statistical power analysis was performed on the large effect size (η_p^2 = .2, which equals f = 0.5) and correlation among repeated measures = .5 as found in previous data. The necessary sample size when comparing only two groups in a repeated-measures (two-levels) ANOVA targeting a between-factor effect and ensuring alpha = .05 and power = .80 was N = 26 (thirteen per group).

Of the initially acquired 35 data sets, the recordings of 22 participants (11 females) remained in the analysis after excluding all recordings with technical issues or of participants that had been familiar with 50% or more of the route. The remaining participants had a mean route familiarity of 9.52% (*SD* = 12.2%) with comparable values for the different navigation instruction groups (standard: *M* = 11.5%, *SE* = 3.72%, long: *M* = 7.50%, *SE* = 3.72%, $F(1,20)$ = 0.59, p = .451, η_p^2= .029). All participants were naïve to the tasks and none had participated in the other experiments. The age ranged between 20 and 39 years (*M* = 27.4 years, *SD* = 4.63 years). Each experimental condition consisted of eleven participants with gender being balanced across conditions. Recruitment of participants was done using an existing database or personal contacts and participants received reimbursement or course credit. All participants had normal or corrected to normal vision and gave written informed consent prior to the study. The study was approved by the local ethics committee.

3.1.2 Procedure

Like the first experiment, this experiment took place in two sessions directly following each other. A short break of about 15min between the assisted navigation phase and the subsequent spatial tests was necessary for transporting the participant from the end of the route to the laboratory. The experiment lasted about 3 hours in total. During assisted navigation, participants navigated the identical route presented as video in Experiment 1 with a predefined route through an urban environment, the district of Charlottenburg, Berlin in Germany. Two navigation instruction conditions were tested with the control group receiving standard navigation instructions and a second group receiving the long landmark-based navigation instructions as used in Experiment 1. Participants were unaware that they would be tested about the navigated environment after the navigation phase.

Figure 4: ***Experimental setup of Experiment 2***
a) Real-world setup of the navigation task in Experiment 2. The experimenter followed the participant and initiated the auditory navigation instructions. b) Identical landmark pictures as in the cued-recall task of Experiment 1 were used in the cued-recall task of Experiment 2. The right picture displays one example landmark at an intersection ("public restroom") with a similar perspective as encountered during navigation (pictures were presented in color during the cued-recall task).

3.1.3 Navigation phase

Each participant came to the Berlin Mobil Brain/Body Imaging Lab (BeMoBIL) to receive all necessary information about the experiment and to sign the informed written consent. They were then transported by car to the starting point of the route. Upon arrival, the EEG cap (eego, ANT Neuro, Enschede, Netherlands) was applied. Participants were instructed to follow the guidance of the auditory navigation instructions, to be attentive to the surrounding traffic at all times, and to stop when they felt lost. An experimenter was following the participant during navigation to ensure that the participant would safely walk the correct route (see Figure 4a). The auditory navigation instructions were triggered manually by the experimenter at predefined trigger points alongside the route. For doing so, a customized browser-based application was developed which was controlled by a smartphone. Participants as well as the experimenter were provided with the auditory navigation instructions via Bluetooth headphones (Cheetah Sport In-Ear, Mpow, Hong Kong, China).

After navigation, participants rated their subjective navigation task-related load by answering the NASA-TLX (Hart, 2006; Hart & Staveland, 1988). Furthermore, participants responded to questions regarding route familiarity and in case they were part of the landmark-based instruction group, the acceptance of the modified navigation instructions.

3.1.4 Test phase

After the navigation phase, participants were transported back to the BeMoBIL providing a controlled laboratory setting for the spatial test session. A sketch map task as well as the cued-recall task had to be solved, followed by a digital version of the PTSOT (Hegarty & Waller, 2004, https://github.com/TimDomino/ptsot). During the tasks, participants were seated at a table and used paper and pen for the sketch map task or the keyboard for the other tasks. Participants were still wearing the EEG cap in order to record brain activity during the spatial tasks as well.

The cued-recall task was identical with the one of Experiment 1, the same 60 screen captures from the video were used as landmark pictures including twenty pictures of each landmark type. Pictures of landmarks displayed their surroundings in the first-person perspective during walking (see Figure 4b). Every landmark picture was shown for three seconds and then a picture with the four possible response keys replaced the landmark picture until response. After each response, participants were asked to rate how confident they had been about their answer on a six-point scale ranging from "1 - very sure" to "6 - I did not know" or to choose a seventh option stating 'I know that my last response was wrong'. Subsequent to the tasks, questionnaires were used to collect demographic characteristics, individual navigation preferences, and the self-reported SOD.

3.1.5 Statistical analysis

A mixed measures ANOVA tested recognition sensitivity using the navigation instruction condition (standard, long) as between-subject factor and landmark type (intersections, straight segments) as within-subject factor. The percentage of correct responses for landmarks at intersections was tested by a one-factorial ANOVA with the between-subject factor navigation instruction condition (standard, long).

In case an individual measure correlated significantly with the dependent variable for each within-subject factor level, it was included as a covariate in the respective analysis. For additional information please see methods part of Experiment 1.

3.2 Results

3.2.1 Individual measures

Averaged across all participants, a mean error deviation angle in the PTSOT of 31.4° (*SD* = 24.5°) showed no differences between the navigation instruction groups (standard: *M* = 36.4°, *SE* = 7.40°, long: *M* = 26.5°, *SE* = 7.40°, $F(1,20) = 0.91$, $p = .352$, $\eta_p^2 = .043$). Comparable group means were observed for the self-reported SOD with an overall mean of 3.73 (*SD* = 1.49) and group means (standard: *M* = 3.36, *SE* = 0.44, long: *M* = 4.09, *SE* = 0.44, $F(1,20) = 1.34$, $p = .261$, $\eta_p^2 = .063$). Participants stated their subjective mental load after assisted navigation on a scale from 1 to 100 with *M* = 30.0 (*SD* = 18.5, standard: *M* = 22.6, *SE* = 5.22, long: *M* = 37.5, *SE* = 5.22, $F(1,20) = 4.04$, $p = .058$, $\eta_p^2 = .168$).

The Spearman correlation of the angular error in the PTSOT showed a significant correlation with the percentage of correct responses to landmarks at intersections (ρ = -.504, p = .017, all other $|\rho|$'s < .297, p's > .181). The correlation of the SOD rating and the percentage of correct responses to each landmark type was not significant ($|\rho|$'s < .337, p's > .126). The subjective mental load correlated positively with the sensitivity d' for landmarks at intersections (ρ = .457, p = .033, all other $|\rho|$'s < .334, p's > .129). As the non-significant correlation of subjective mental load with the recognition sensitivity for landmarks at straight segments pointed in the opposite direction (ρ = -.270), subjective mental load did not fulfill the requirements to be entered as a covariate. Thus, only the PTSOT error was included as covariate in the one-factorial ANOVA testing the percentage of correct responses regarding landmarks at intersections.

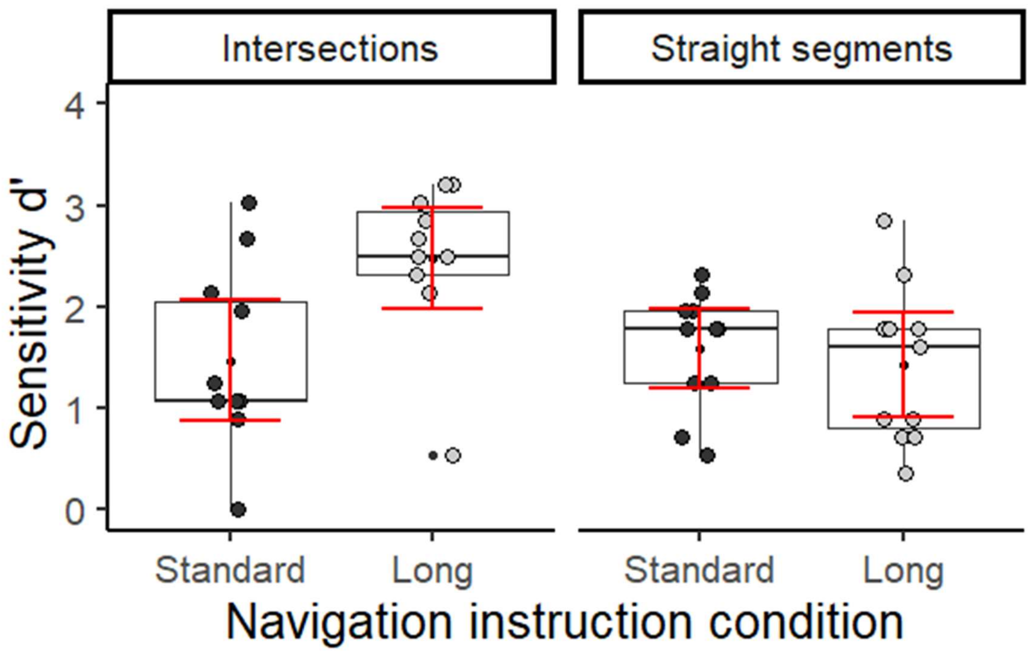

Figure 5: ***Recognition sensitivity in Experiment 2***
The recognition sensitivity for correctly recognizing familiar landmarks presented as box plots with single subject values of d' and red error bars representing the 95% CI of the mean. d' equals the z-standardized false alarm rate subtracted from the z-standardized hit rate. The left column displays recognition sensitivity for landmarks at intersections and the right column displays recognition sensitivity for landmarks at straight segments.

3.2.2 Landmark knowledge

Recognition sensitivity for landmarks at intersections and at straight segments is displayed in Figure 5. When testing the recognition sensitivity, the main effect of landmark type ($F(1,20)$ = 4.22, p = .053, η_p^2 = .174) and the main effect of navigation instruction condition ($F(1,20)$ = 3.53, p = .075, η_p^2 = .150) did not reach significance. However, there was a significant interaction of both factors ($F(1,20)$ = 6.51, p = .019,

η_p^2 = .246). The post-hoc comparisons of the interaction comparing the navigation instruction conditions for each landmark type revealed a significantly lower sensitivity for landmarks at intersections in the standard navigation instruction group (*M* = 1.47, *SE* = 0.25) compared to the landmark-based navigation instruction group (*M* = 2.47, *SE* = 0.25, *p* = .009, 95% CI [-1.73 -0.28]).

3.2.3 Route knowledge

The ANCOVA for the percentage of correctly identified landmarks at intersections and associated navigation decision revealed a significant main effect of the covariate PTSOT error ($F(1,19)$ = 6.84, *p* = .017, η_p^2 = .265) as well as a significant main effect of the factor navigation instruction ($F(1,19)$ = 10.0, *p* = .005, η_p^2 = .346, 95% CI [7.34 31.7]). Post-hoc comparisons revealed the control group to identify less route directions related to the presented landmarks correctly (*M* = 49.6%, *SE* = 3.68%) compared to the long landmark-based navigation instruction condition (*M* = 69.1%, *SE* = 3.68%). In Figure 6, individual performance scores were presented.

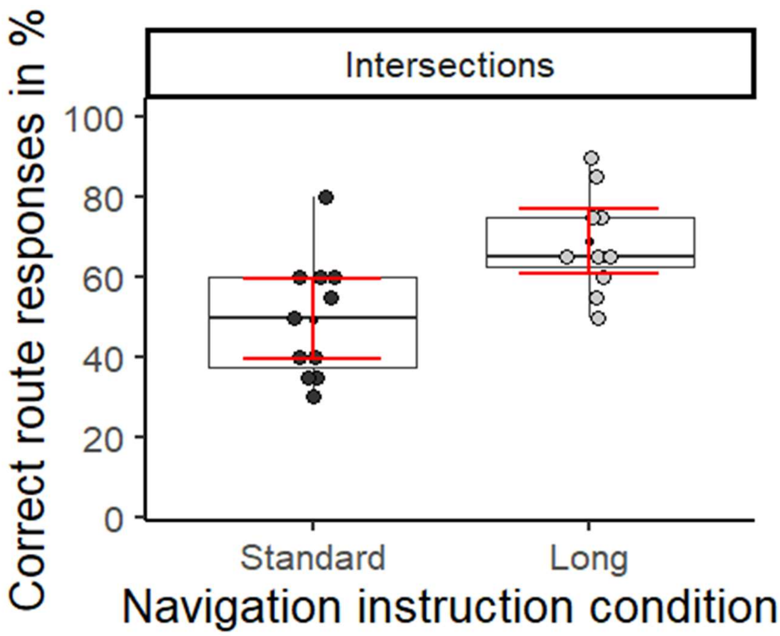

Figure 6: ***Acquired route knowledge in Experiment 2***
Boxplots and single subject performance scores represent the percentage of correctly indicated route direction after presentation of landmarks located at intersections during the cued-recall task. Red error bars depict the 95% CI of the mean. The performance measure could reach twenty different values with a step-width of 5% reaching 100% when responses to all twenty landmarks at intersections were correct.

3.2.4 Confidence Ratings

Participants rated their confidence on a six-point scale ranging from "1 - very sure" to

“6 - I did not know” with an overall mean of M = 2.86 (SD = 0.49). Navigation instruction groups did not differ regarding their confidence ratings (standard: M = 2.88, SD = 0.45, long: M = 2.83, SD = 0.54, $F(1,20)$ = 0.07, p = .795, η_p^2 = .003).

3.3 Discussion

Experiment 2 tested the incidental spatial knowledge acquisition during assisted pedestrian navigation in an uncontrolled, dynamically changing real-world setting including cars and other pedestrians. Performance in the cued-recall task was tested directly following the assisted navigation phase. The results replicated previous findings supporting the assumption that landmark-based navigation instructions enhance incidental spatial knowledge acquisition during assisted navigation.

The recognition sensitivity was overall increased compared to video navigation and, in accordance with our hypothesis, indicated enhanced spatial knowledge acquisition for landmark-based navigation instruction during real world navigation. The significant interaction effect of landmark type and navigation instruction conditions showed that participants receiving long landmark-based navigation instructions acquired more landmark knowledge at intersections than the control group.

When testing incidentally acquired route knowledge by considering only correct direction responses, the performance was slightly better than in video navigation. The long instruction condition again outperformed the standard navigation instruction condition. Even though there was a significant correlation of correct responses for landmarks at intersections and the individual perspective taking ability (PTSOT), the covariate did not diminish the effect of navigation instruction conditions. Thus, it can be concluded that even though perspective taking ability seems to modulate spatial knowledge acquisition during assisted navigation on a route level, an additional impact of landmark-based navigation instructions can be observed.

A significantly higher recognition sensitivity for landmarks at intersections compared to straight segments was observed when using landmark-based navigation instructions. The landmark-based navigation instructions did not lead to a better recognition of other landmarks along the route in between intersections. This result contrasts with the results from Experiment 1 which revealed a comparable recognition sensitivity for landmarks at straight segments and landmarks at intersections for all tested instruction conditions. Confidence ratings after cued-recall responses were slightly lower compared to video-navigation and in general only rather confident with again no difference between navigation instruction conditions.

4 Experiment 3

The third experiment took place again in an unrestricted, real-life setting. The experimental setting was modified by extending the route and adding a two-week break between assisted navigation and testing the acquired spatial knowledge. This way, the third experiment aimed at replicating Experiment 2 and testing the previously shown long-term effect of Wunderlich and Gramann (2018) in a setting providing full ecological validity. Additionally, the perspective of the landmark pictures in the cued-recall task was changed to a frontal view in order to test the quality of the incidentally acquired landmark and route knowledge. Physiological measures were recorded during the spatial tasks and results will be reported elsewhere.

4.1 Material and methods

4.1.1 Participants

In this experiment, the sample size was based on the same a priori power analysis as reported in Experiment 1. In total 41 participants were recorded during real-world navigation. All participants were naïve to the tasks and no one had participated in any of the previous experiments. Due to technical issues or familiarity with 50% or more of the route, six of the participants had to be removed from the database. The remaining 35 participants (20 females) were aged between 20 and 34 years (*M* = 26.7 years, *SD* = 3.08 years) and stated their prior route familiarity with *M* = 15.4% (*SD* = 13.1%, standard: *M* = 17.9%, *SE* = 3.81%, short: *M* = 11.5%, *SE* = 3.81%, long: *M* = 17.0%, *SE* = 3.98%, $F(2,32) = 0.82$, $p = .448$, $\eta_p^2 = .049$). Each participant was randomly assigned to an experimental condition (standard instructions: 8 female, 4 male; short instructions: 6 female, 6 male; long instructions: 6 female and 5 male participants). Participants were recruited through an existing database or personal contact and were reimbursed monetarily or received course credit. All had normal or corrected to normal vision and gave written informed consent prior to the study. The study was approved by the local ethics committee.

4.1.2 Procedure

The experiment was scheduled in two sessions separated by a break of two weeks. Taken together, both experimental sessions lasted about 3 hours and 30 minutes. In the first part, participants navigated along a predefined route through an urban environment, the district of Charlottenburg, Berlin in Germany. The route overlapped with the route in Experiment 1 and 2. Each participant was guided by auditory navigation instructions. There were three groups of participants including a control group who received standard navigation instructions. The landmark-based navigation instruction groups were either receiving the short, or long landmark-based navigation instructions. After a break of two-weeks (13 to 17 days, *M* = 14.1 days, *SD* = 0.73 days), the participants were invited to return and to solve spatial tasks in a laboratory setting. Participants were informed about the second session without providing information about its content. The relatively long break between navigation and test phase allowed for investigating the generalizability of the previously reported long-term impact of landmark based navigation instructions on spatial knowledge acquisition (Wunderlich & Gramann, 2018). Importantly, and in contrast to Wunderlich and Gramann (2018), participants walked through a city environment during the navigation phase and were also moving through the same city during their daily activities between navigation and test phase. Thus, they were probably experiencing a similar city environment that interfered with spatial knowledge about the experimental route. This way, the experiment represents an ecologically valid case of long-term spatial knowledge acquisition during assisted navigation.

Figure 7: ***Experimental setup of Experiment 3***
a) Real-world setup of the navigation task in Experiment 3. The experimenter followed the participant and initiated the auditory navigation instructions. b) Frontal view picture of a navigation relevant landmark ("public restroom") as used in the cued-recall task (pictures were presented in color).

4.1.3 Navigation phase

An experimenter met each participant at a train station and guided them to the starting point of the route. There, participants were informed about the upcoming navigation task. They were instructed to follow the auditory navigation instructions, to pay attention to the traffic while crossing streets, and to stop in case they did not know which direction to proceed. While navigating the route, an experimenter was walking in the vicinity of the participant to intervene in case of hazards and ensure that the participant would follow the correct route (see Figure 4a). The experimenter also manually triggered the auditory navigation instructions at predefined trigger points alongside the route using a browser-based application on a smartphone. The auditory navigation instructions were provided to both, the participant and the experimenter, via Bluetooth headphones (Cheetah Sport In-Ear, Mpow, Hong Kong, China). The route consisted of 40 intersections including 22 direction changes. Participants arrived at the end of the route after walking approximately 60 minutes.

Following the navigation phase, navigators provided their subjective rating of the navigation task-related load as assessed using the NASA-TLX (Hart, 2006; Hart &

Staveland, 1988). In addition, participants answered questions about route familiarity and acceptance of the modified navigation instructions.

4.1.4 Test phase

During the spatial test session in a controlled laboratory setting, the cued-recall task and a video-turn task were recorded. Before the two tasks, participants were equipped with EEG (BrainAmps, Brain Products, Gilching, Germany) and seated at a table in front of a computer screen and keyboard. Analog to the cued-recall task of Experiment 1 and 2, 120 landmark pictures were presented including forty pictures of each landmark type. Pictures displayed their surroundings but in contrast to Experiments 1 and 2, landmarks were presented in a front view perspective (see Figure 7b compared to Figure 1b and Figure 4b). Novel landmark pictures were photographs taken in a similar way and similar weather conditions in a neighboring area. Every landmark picture was shown until the participant responded by pressing one of the four possible arrow keys. After each response, participants were asked to rate how confident they had been about their answer on a six-point scale ranging from “1 - very sure” to “6 - I did not know”. After the tasks, questionnaire data was collected including demographic characteristics, individual navigation styles, and self-reported SOD.

4.1.5 Statistical analysis

As in Experiment 1, two analyses of variance were computed to test whether landmark-based navigation instructions led to better landmark and route knowledge. Investigating the acquired spatial knowledge, a mixed measures ANOVA tested the recognition sensitivity with the between-subject factor navigation instruction condition (standard, short, long) and the repeated measures factor landmark type (intersections, straight segments). Additionally, the percentage of correct responses for landmarks at intersections was tested in a one-way ANOVA comparing the three navigation instruction conditions. For additional information, please see methods part of Experiment 1.

4.2 Results

4.2.1 Individual measures

Overall, participants rated their sense of direction with M = 4.29 (SD = 1.74). The instruction group means differed (standard: M = 3.33, SE = 0.47, short: M = 5.17, SE = 0.47, long: M = 4.36, SE = 0.49, $F(2,32)$ = 3.91, p = .030, η_p^2 = .196) with values of the short navigation instruction group being significantly higher than the mean in the standard instruction group (p = .026, 95% CI [0.17 3.49] other p’s > .404).

The subjective mental load during assisted navigation was on average 15.0 (SD = 9.32, data missing for 14 participants). The Spearman correlations of the SOD rating and the subjective mental load with the dependent variables were not significant

($|\rho|$'s < .239, p's > .300). Thus, neither the SOD rating nor the subjective mental load were included as covariate in the analyses.

4.2.2 Landmark knowledge

Individual and group values of recognition sensitivity are presented in Figure 8. The ANOVA testing the recognition sensitivity revealed a main effect of landmark type ($F(1,32) = 142$, $p < .001$, $\eta_p^2 = .817$) and a main effect of navigation instruction condition ($F(2,32) = 5.31$, $p = .010$, $\eta_p^2 = .249$). In addition, the interaction of both factors was significant ($F(2,32) = 4.07$, $p = .027$, $\eta_p^2 = .203$). The recognition sensitivity for landmarks at intersections (M = 1.66, SE = 0.12) was significantly higher compared to landmarks at straight segments (M = 0.20, SE = 0.14, $p < .001$, 95% CI [1.36 1.92]). The control group had significantly lower d' (M = 0.33, SE = 0.19) than the landmark-based navigation instruction conditions (short: M = 1.13, SE = 0.19, p = .017, 95% CI [-1.48 -0.12]; long: M = 1.06, SE = 0.20, p = .039, 95% CI [-1.48 -0.03]). Short and long navigation instruction conditions were comparable (p > .999). The post-hoc comparisons of the interaction comparing the navigation instruction conditions for each landmark type revealed a lower recognition sensitivity for landmarks at intersections in the standard navigation instruction group (M = 0.90, SE = 0.21) compared to the landmark-based navigation instruction groups (short: M = 1.98, SE = 0.21, $p < .001$, 95% CI [-1.82 -0.35]; long: M = 2.10, SE = 0.22, $p < .001$, 95% CI [-1.95 -0.45]). All other p's were above .093.

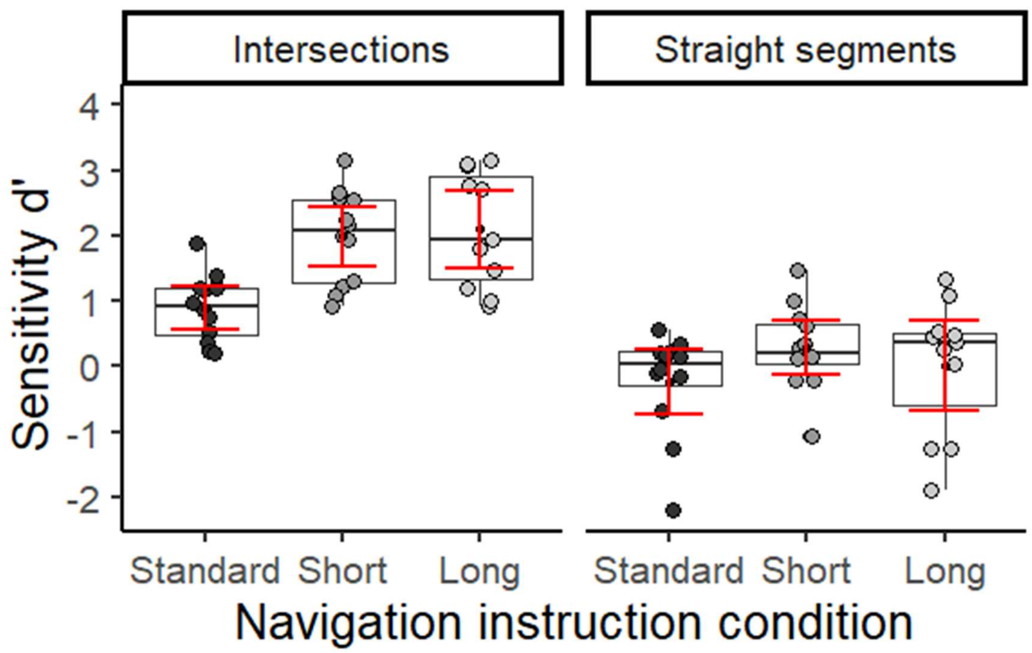

Figure 8: ***Recognition sensitivity in Experiment 3***

The recognition sensitivity for correctly recognizing familiar landmarks presented as box plots with single subject values of d' and red error bars representing the 95% CI of the mean. d' equals the z-standardized false alarm rate subtracted from the z-standardized hit rate. The left column displays recognition sensitivity for landmarks at intersections and the right column displays recognition sensitivity for landmarks at *straight segments.*

4.2.3 Route knowledge

The one-way ANOVA comparing the percentage of correct responses to the landmarks at intersections between the three navigation instruction conditions revealed a significant difference ($F(2,32) = 6.07$, $p = .006$, $\eta_p^2 = .275$). The standard navigation instruction condition had a significantly lower performance (*M* = 30.2%, *SE* = 3.45%) as compared to the landmark-based navigation instruction condition (short: *M* = 42.9%, *SE* = 3.45%, *p* = .041, 95% CI [0.73 24.7]; long: *M* = 46.6%, *SE* = 3.60%, *p* = .007, 95% CI [4.14 28.6]). Performance of short and long navigation instruction conditions demonstrated comparable results ($p > .999$). Distribution and individual performance scores are displayed in Figure 9.

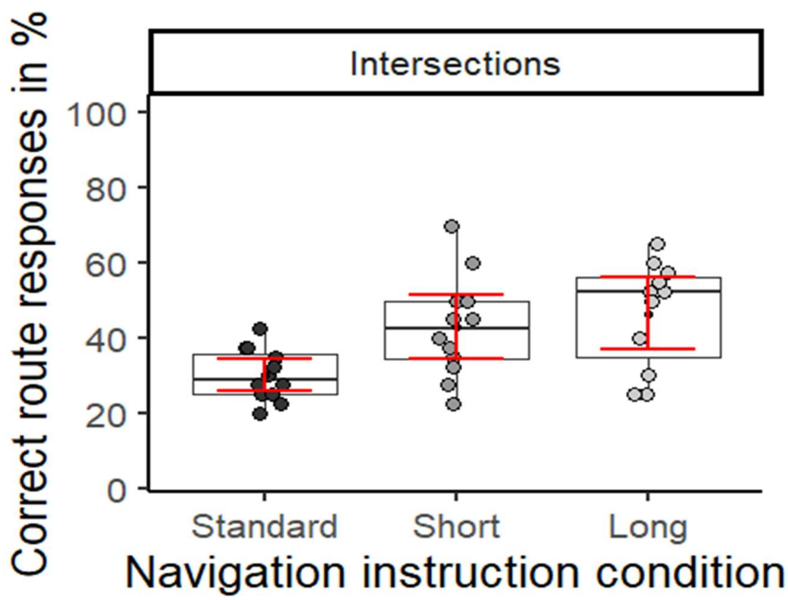

Figure 9: ***Acquired route knowledge in Experiment 3***
Boxplots and single subject performance scores represent the percentage of correctly indicated route direction after presentation of landmarks located at intersections during the cued-recall task. Red error bars depict the 95% CI of the mean. The performance measure could reach forty different values with a step-width of 2.5% reaching 100% when responses to all forty landmarks at intersections were correct.

4.2.4 Confidence Ratings

Participants rated their confidence on a six-point scale ranging from "1 - very sure" to "6 - I did not know" with an overall mean of *M* = 3.26 (*SD* = 0.61). Navigation instruction groups did differ significantly (standard: *M* = 3.69, *SD* = 0.44, short: *M* = 3.22, *SD* = 0.49, long: *M* = 2.83, *SD* = 0.60, $F(2,32) = 9.27$, $p = .001$, $\eta_p^2 = .367$). Participants in the long navigation instruction condition reported higher confidence in their responses compared to those of the standard navigation instruction condition ($p = .001$, 95% CI [-1.40 -0.38]). The other post-hoc comparisons were non-significant (p's > .096).

4.3 Discussion

Experiment 3 followed up on Experiment 2 investigating the durability of incidental spatial knowledge acquisition during assisted pedestrian navigation in the real world. When tested two weeks after the assisted navigation, the overall recognition sensitivity for landmarks at intersections remained on a moderate level whereas the recognition sensitivity for straight segments dropped to chance level and the percentage of correct direction responses decreased twenty percentage points. However, the long break uncovers the advantage of landmark-based navigation instructions even more.

When investigating the recognition sensitivity with signal-detection theory, we observed good performance for landmarks at intersections in the landmark-based condition as compared to a moderate recognition sensitivity for standard navigation instructions. Landmark-based navigation instructions also led to better route knowledge as reflected in the percentage of correct direction responses. However, long and short landmark-based instructions did not differ with regards to acquired route knowledge. It can thus be concluded that after a break of two-weeks the advantage of long versus short navigation instructions as seen in the video-based results disappears and both navigation instructions perform better than standard instruction but comparably regarding the successful recollection of landmark and route knowledge.

As in Experiment 2, the recognition sensitivity was significantly higher for the referenced landmarks at intersections compared to salient objects at straight segments after navigating with landmark-based navigation instructions. In contrast to all previous experiments, landmark pictures were presented from a frontal view instead of a navigators' perspective when navigating through the environment. This might have been especially detrimental to the recognition of landmarks positioned at straight segments as participants might not have turned their heads to inspect all buildings alongside the route and thus, landmarks at straight segments were less likely encountered from this perspective. When approaching an intersection or crossing a street turning the head to left and right is a well-trained behavior essential for maintaining safety. That is why, participants of all navigation instruction conditions likely have processed landmarks at intersections from more than one perspective leading to better recognition performances. This may also be partly reflected in the confidence rating after each direction response. Overall, participants were ambiguous in their confidence statement which also could be explained by the two-weeks break. For the first time the confidence ratings differed between navigation instruction conditions with participants of the long navigation instruction condition being rather confident about their responses whereas participants who had received standard navigation instructions were rather unconfident about their direction responses. Short navigation instructions resided in between the other two conditions. Thus, even though the more detailed landmark-based navigation did not lead to objectively better performance, it led to higher confidence which can be an important factor in safely navigating an unfamiliar, dynamic environment.

A limitation of Experiment 3 is missing data and group differences regarding the individual measures. The subjective task load was only collected from a subset of the sample and the individual perspective taking ability was not tested. In Experiment 1 and 2, a significant impact of individual perspective taking on acquired landmark or route knowledge was shown. However, this impact did not explain or diminish the effect of navigation instruction conditions. The self-reported sense of direction differed significantly between the standard and short navigation instruction condition, but not compared to the long navigation instruction condition. Thus, it is possible that group differences between standard and short could be explained by the SOD rating. However, the missing correlation of the SOD rating with the dependent variables and the comparable results of the two landmark-based navigation instruction when testing the spatial knowledge measures counter this assumption.

To sum up, when pedestrians used landmark-based navigation instructions in the real-world environment, they acquired more spatial knowledge about the travelled environment, especially about the auditorily referenced landmarks at intersections, and were more confident in their responses. This advantage was still measurable after two weeks replicating the long-term effects previously shown in simulated driving through a sparse and controlled virtual world by Wunderlich and Gramann (2018). This long-term improvement took place even though participants possibly commuted through a similar city environment in the time period between navigation and test phase, potentially interfering with memory consolidation.

5 General Discussion

A series of experiments investigated incidental spatial knowledge acquisition during assisted pedestrian navigation in ecologically valid scenarios. It was investigated whether there is evidence for enhanced incidental spatial knowledge acquisition when using different versions of landmark-based navigation instructions and whether these also change the processing of the environment in general. To that end, three experiments were conducted investigating the performance in a cued-recall task as an indicator for landmark- and route-level spatial knowledge acquired during a single exposure to an unfamiliar environment. The navigation contexts used were videos of (Experiment 1) as well as real-world pedestrian navigation (Experiment 2 and 3) through an unfamiliar city area. In summary, enhanced incidental spatial knowledge acquisition was shown for landmark-based navigation instructions in all three experiments. But there was no hint of a generalization of spatial knowledge acquisition beyond the referenced landmarks to other salient objects in the environment. Thus, no effect of landmark-based navigation instructions reflecting a generally increased processing of the environment was observed. Individual measures for spatial abilities and mental load were controlled for and did not impact the effects of the navigation instruction conditions on spatial knowledge acquisition.

Decreased spatial memory performance had been associated with the use of navigation aids and is likely caused by divided attention between the control of movement and the navigation assistance (Gardony et al., 2013; Gardony et al., 2015). Whether spatial knowledge acquisition would be impaired when using standard navigation instructions irrespective of the course of the route (approaching intersections versus walking straight segments) was not yet investigated. In the studies of Gardony and colleagues, only the retrieval of landmarks at intersections was examined. Here, comparing spatial knowledge for different landmark types, we still found poorer landmark knowledge at intersections for the standard navigation instruction condition while having comparable landmark knowledge for landmarks at straight segments. The reduced spatial knowledge acquisition was likely caused by navigation instructions biasing the attention towards the turn itself while landmark-based navigation instructions helped to process environmental features. The augmentation of landmarks allowed to encode a specific landmark in association with a turning decision.

The results of all three experiments replicated the positive impact of landmark-based navigation instructions on spatial knowledge acquisition which was previously shown for visual landmark augmentation (Krukar et al., 2020; Li et al., 2014; Löwen et al., 2019; Tom & Denis, 2003). Furthermore, the reported experiments replicated findings from Gramann and colleagues (2017) and Wunderlich and Gramann (2018) demonstrating an increased cued-recall performance especially regarding landmarks at intersections after navigating with auditory landmark-based navigation instructions. This underpins the robustness and the ecological validity of the reported incidental spatial learning effect when using landmark information in auditory navigation instructions.

The acquired landmark and route knowledge did not depend on individual spatial abilities demonstrating that landmark-based navigation instructions improve spatial knowledge acquisition for all navigators irrespective of their spatial abilities. Even though an impact of individual perspective taking ability on spatial knowledge acquisition was revealed, this effect did not explain the increased spatial knowledge acquisition based on the landmark-based navigation instructions.

In addition, the results provided evidence that adding detailed information about a landmark in addition to a landmark name is similar to the personal preference navigation instruction condition used in Gramann and colleagues (2017) and Wunderlich and Gramann (2018) regarding spatial knowledge acquisition. In Experiment 1, only an advantage of long landmark-based navigation instructions was found for incidental route knowledge acquisition. It was beneficial to add semantic information in the auditory navigation instructions. Only naming the landmark was not sufficient. It can be argued that the detailed information about the landmarks in long navigation instructions may have helped to identify the landmark and this way eased the landmark recognition in the cued-recall task. However, the additional semantic information was mostly related to the function of the object and did not include characteristics that were visible (e.g., "Go straight at the Malteser building. This aid organization counts one million members.") As such, the identification of landmarks was similar in both landmark-based navigation instructions and a confounding effect can be ruled out. In Experiment 3 testing spatial knowledge after a break of two weeks, no difference between the landmark-based navigation instructions was measurable, but both modifications significantly improved the incidentally acquired spatial knowledge compared to the control group. This replicates the driving simulator studies (Gramann et al., 2017; Wunderlich & Gramann, 2018) and hints at a significant impact of landmark references in navigation instructions but only a rather short-term and subjectively experienced advantage of the following more detailed landmark information when tested in real-world pedestrian navigation.

Furthermore, it can be argued that the landmark pictures used in the cued-recall task were simply showing the wrong environmental features and in turn led to the lower performance of the control group receiving standard navigation instructions. This is a valid argument, but the used pictures displayed the landmarks in context, so that also other environmental features at intersections could serve as landmarks and lead to correct responses. The moderate recognition sensitivity for landmarks at intersections of the standard navigation instruction condition emphasizes that the choice of landmarks for the cued-recall likely overlapped with the presented images. This is further supported by the results of the recognition sensitivity for landmarks at straight segments which was above chance and similar for all navigation instruction conditions when tested directly after assisted navigation.

Another hypothesis based on the brain activity results of Wunderlich and Gramann (2018) was that landmark-based instructions lead to a generally increased allocation of attention towards the environment. This would be supported when the navigation instructions at relevant navigation points like intersections also impacted how the surroundings were processed during straight segments where no navigation instructions were provided. The comparable recognition rates for landmarks at straight segments across navigation instruction conditions in all experiments, however, did not support such a general effect of landmark augmentation.

An interpretation of all reported results is still restricted to the investigation of acquired spatial knowledge when navigating one route in an unfamiliar environment. Thus, the spatial representation remains on a rather coarse level consisting primarily of landmark and basic route knowledge. A generalization to spatial knowledge acquisition based on multiple uses of landmark-based navigation instructions for the same route or different routes with overlap is not yet possible. However, the results let us expect that spatial knowledge acquisition would be enhanced even more. Multiple use of landmark-based navigation assistance in the same area would also ease the assessment of acquired survey knowledge. It was shown that landmark, route and survey knowledge develop in parallel, rather than in a sequential fashion revealing increasing convergence with increasing exposure to the same environment (Buchner & Jansen-Osmann, 2008; Kim & Bock, 2020). Fostering the acquisition of survey knowledge would be the ultimate goal of a learning-oriented navigation assistance systems as survey knowledge would allow for more flexible use of the acquired spatial knowledge (e.g., short cuts). For now, the cued-recall performance allows only for conclusions about the acquired landmark and route level knowledge, but not survey knowledge. Whether the landmark-based navigation instructions can help to improve survey knowledge after repetitive use of the system in the same environment has yet to be tested.

In summary, this series of experiments demonstrated improved landmark and route knowledge acquisition during assisted navigation including both the transfer from low to high realism of the environment as well as the realism of the movement through the environment, and investigating the durability of the acquired knowledge allowing for interfering navigation experiences. Despite all setup changes, the results indicate that landmark-based navigation instructions lead to improved spatial knowledge acquisition compared to standard navigation instructions that are currently used as default in available navigation assistance systems.

6 Conclusions

The findings of the three experiments reported here replicated the previously described increased incidental spatial knowledge acquisition associated with landmark-based navigation instructions. This effect was shown to be generalizable across different navigation contexts and types of locomotion. Thus, landmark-based navigation instructions are a promising tool to keep the processing of the environment high and foster the extraction of navigation relevant information. Future research should address the multiple use of landmark-based navigation instructions and the accompanying spatial knowledge acquisition. This way, landmark-based navigation assistants may train the users' orientation abilities enabling them to autonomously navigate the environment in the future.

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Highlights

- Auditory landmark references in navigation instructions support spatial learning.
- Spatial learning is incidental and does not impair the primary locomotion task.
- Landmark-based incidental spatial learning is replicable in the lab and real world.

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Data Availability

Data were collected at TU Berlin. The data of single or all experiments are available on request from the corresponding author AW.

Author Contributions

A.W.: data curation, formal analysis, methodology, software, visualization, writing - original draft and review; K.G.: conceptualization, resources, supervision, writing - review and editing.

Conflict of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.