Overcoming Spatial Deskilling Using Landmark-Based Navigation Assistance Systems

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Abstract

Background. The repeated use of navigation assistance systems leads to decreased spatial orienting abilities. Previous studies demonstrated that augmentation of landmarks using auditory navigation instructions can improve incidental spatial learning when driving on a single route through an unfamiliar environment.

Objective. Based on these results, a series of experiments was conducted to further investigate both the impairment of spatial knowledge acquisition by standard navigation instructions and the positive impact of landmark augmentation in auditory navigation instructions on incidental spatial learning.

Method. The first Experiment replicated the previous setup in a driving simulator without additional visual route indicators. In a second experiment, spatial knowledge was tested after watching a video depicting assisted navigation along a real-world urban route. Finally, a third Experiment investigated incidental spatial knowledge acquisition when participants actively navigated through an unrestricted real-world, urban environment.

Results. All three experiments demonstrated better cued-recall performance for participants navigating with landmark-based auditory navigation instructions as compared to standard instructions. Notably, standard instructions were associated with reduced learning of landmarks at navigation relevant intersections as compared to landmarks alongside straight segments and the recognition of novel landmarks.

Conclusion. The results revealed a suppression of spatial learning by established navigation instructions, which were overcome by landmark-based navigation instructions. This emphasizes the positive impact of auditory landmark augmentation on incidental spatial learning and its generalizability to real-life settings.

Application. This research is paving the way for navigation assistants that, instead of impairing orienting abilities, incidentally foster spatial learning during every-day navigation.

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

Précis: This series of three experiments replicates the suppression of spatial learning by standard navigation instructions and the positive impact of landmark augmentation in auditory navigation instructions on incidental spatial learning during assisted navigation. Three experiments with growing degree of realism revealed the applicability and generalizability to real-life settings.

Introduction

Navigation aids providing visual as well as auditory guidance as a support (Allen, 1999) during wayfinding through known and unknown environments have become common everyday tools (Axon, Speake, & Crawford, 2012; Kalin & Frith, 2016; Kitchin & Dodge, 2007). The pedestrians' use of hand-held navigation devices has increased over the last decade. In 2018, more than 50% of the surveyed Americans across all age groups stated that they had used their smartphone for online map or navigation services in the last month (Statista Survey). With the use of navigation aids, wayfinding evolved from analog 2D map-based tasks into digitally assisted instruction following tasks. A recent survey addressing a large representative German population, revealed a stronger trend towards route-based wayfinding strategies as compared to twenty years ago, along with an increasing inability to use any wayfinding strategy among younger adults in comparison to older age groups (Ulrich, Grill, & Flanagin, 2019). This trend towards route-based wayfinding strategies was likely fostered by the increased use of navigation assistance systems, as most navigation aids provide turn-by-turn instructions, biasing a route perspective (Gardony, Brunyé, Mahoney, & Taylor, 2013). Mobile navigation applications and their side effects will likely play an even more central role for the generations growing up with smartphones.

The described developments motivated several studies to investigate the interaction of users with different kinds of navigation aids in order to describe and understand the underlying cognitive processes. One finding was that the use of automated navigation assistance systems was associated with divided attention between the movement related tasks and the assisted navigation (Fenech, Drews, & Bakdash, 2010; Gardony et al., 2013; Gardony, Brunyé, & Taylor, 2015). This seems to increase the reliance on the navigation assistant to reduce the attentional demand (Baus, Kray, & Krüger, 2001; Klippel, Hirtl, & Davies, 2010; Parush, Ahuvia, & Erev, 2007) leading to an automation bias (Lin, Kuehl, Schöning, & Hecht, 2017). Users tend to hand over the decision-making to the automated system (Bakdash, Linkenauger, & Proffitt, 2008; Fenech et al., 2010; Parush et al., 2007; Peruch & Wilson, 2004) and follow the system instructions without checking other available information (Mosier, Skitka, Burdick, & Heers, 1996; Parasuraman, 2000). During assisted navigation, this overreliance leads to a decrease in processing the surrounding environment (Aporta & Higgs, 2005; Leshed, Velden, Rieger, Kot, & Sengers, 2008; Farman, 2013; Hirtle & Raubal, 2013; Huang, Schmidt, & Gartner, 2012; Münzer, Zimmer, Schwalm, & Baus, 2006). With repeated use of navigation assistance systems, the users' ability to autonomously solve the navigation task decreases, revealing a deskilling of orienting abilities (Bertel, Dressel, Kohlberg, & von Jan, 2017; Münzer, Zimmer, & Baus, 2012; Parush, Ahuvia, & Erev, 2007).

To overcome deskilling of spatial abilities when using navigation assistance systems, a variety of methods can be used (Giannopoulos, Kiefer, & Raubal, 2015, Gramann, Hoepner, Karrer-Gauss, 2017). One promising approach to support navigation without endangering the users safety in traffic is the inclusion of environmental information about salient objects, so called landmarks (Evans, Smith, & Pezdek, 1982), in the navigation instructions (Dey, Karahalios, & Fu, 2018; Goodman, Brewster, & Gray, 2005; Li, Fuest, & Schwering, 2014; Löwen, Krukar, Schwering, 2019; May, Ross, Bayer & Burnett, 2001; Raubal & Winter, 2002). Research studying spatial knowledge acquisition during assisted pedestrian navigation in the real world demonstrated that visual augmentation of landmarks in the navigated environment enhances spatial knowledge acquisition (Brügger, Richter, & Fabrikant, 2019; Huang et al. 2012; Münzer et al. 2006; Münzer, Lörch, & Frankenstein, 2019). However, none of the studies investigated auditory navigation instructions. Compared to visual augmentation methods, acoustic navigation instructions have the advantage to be safer as they do not interfere with visual attention on the surrounding area including ongoing traffic or other pedestrians (May & Ross, 2006). Ross, May, and Thompson (2004) investigated landmark-based auditory navigation instructions regarding their usability for pedestrians. The authors demonstrated the effectiveness of landmark-based auditory instructions by the prevention of navigation errors and increased navigator's confidence during navigation, as compared to a control group. Despite these findings, the study by Ross and colleagues did not test for the potential impact of landmark-based auditory navigation instructions on spatial learning.

But this impact was shown in a virtual driving paradigm where highlighting objects at navigation relevant intersections (intersections where the route direction changes) using auditory navigation instructions has led to incidental learning of spatial information (Gramann et al., 2017). This improved spatial learning was still observable when tested three weeks after a single exposure to an unfamiliar environment (Wunderlich & Gramann, 2018). Spatial knowledge acquisition with landmark-based navigation instructions was further found to be associated with changes in brain activity, likely reflecting increased information recollection during cued-recall of landmark- and route knowledge from the navigated environment (Wunderlich & Gramann, 2018). Importantly, the results of both studies showed a significantly reduced recognition performance for navigation relevant landmarks for users of standard navigation instructions compared to users of landmark-based navigation instructions. Moreover, when using standard navigation instructions, recognition of relevant landmarks was reduced compared to navigation irrelevant landmarks (salient objects in between navigation relevant intersections) and novel landmarks (landmarks that were not part of the navigated route). This was pointing to a possible suppression effect caused by instructions that guide the users' attention to the intersection rather than the environment around the intersection. In contrast, the cued-recall performance for relevant landmarks was increased in the landmark-based instruction conditions whereas the other landmark categories remained at a comparable level. These results supported the assumption that the inclusion of landmark information in navigation instructions was associated with directing the users' attention towards environmental features at navigation-relevant intersections which in turn led to incidental spatial learning of these features. As the cued-recall performance of relevant landmarks was not improved beyond the recognition performance for navigation irrelevant and novel landmarks, these results indicated that a learning suppression was overcome rather than that additional spatial learning took place (Gramann et al., 2017). Overcoming spatial learning suppression with landmark-based instructions did not, however, affect the subjective mental load or driving behavior (Gramann et al., 2017; Wunderlich & Gramann, 2018).

In the described previous studies using landmark-based navigation instructions it was not tested to what extent such a learning suppression was fostered by visual navigation cues displayed at navigation relevant intersections. In addition, it remained an open question whether improved incidental spatial learning in virtual driving simulations can be generalized to more realistic environments. To overcome these restrictions, we investigated the question whether standard navigation instructions suppress incidental spatial knowledge acquisition for navigation-relevant decision points and if landmark-based instructions lead to an alleviation of this suppression in three consecutive experiments. To this end, cued-recall performance was analyzed combining a test of landmark and route knowledge (Siegel & White, 1975) after navigation. We aimed at investigating incidental spatial knowledge acquisition during assisted navigation including two research questions: a) whether a suppression effect of standard navigation instructions would lead to reduced cued-recall performance for relevant landmarks compared to navigation irrelevant and novel landmarks and b) whether the advantage of landmark-based instructions can overcome this deterioration in spatial knowledge acquisition. This was tested by using standard and landmark-based auditory navigation instructions and three different scenarios ranging from well-controlled simulator driving to pedestrian navigation in a real urban environment. In addition, different versions of landmark-based instructions were investigated to test for the impact of the information quality and quantity about landmarks on spatial learning.

Previous experiments took place in a driving context using a highly controlled and restricted driving simulator setup (Gramann et al., 2017; Wunderlich & Gramann, 2018). This included a more artificial, simulated driving scenario lacking proper self-motion, other traffic participants, and natural visual information. In addition, a visual route indicator was displayed together with the auditory navigation instructions providing multimodal sensory input at intersections. To overcome the experimental limitations of previous studies, the three experiments were conducted to investigate the potential impact of more realistic navigation scenarios as well as the impact of additional visual information on spatial knowledge acquisition during navigation. The first Experiment focused on the impact of the visual route indicator to investigate whether this semi-transparent, projected arrow overlaying the environment contributed to the observed suppression of incidental spatial learning. Moreover, to see whether the reported improvement of incidental spatial knowledge acquisition can be generalized to more naturalistic scenarios, we investigated the impact of modified navigation instructions in realistic environments. The investigation of the generalizability and ecological validity was done in two steps. In Experiment 2, the navigation paradigm was transferred to a pedestrian context. An interactive movie was created showing a pedestrian's first person perspective while navigating through the city of Berlin, Germany, containing other traffic participants and real-world visuals. This allowed high realism while controlling the stimulus material across all participants. Experiment 3 then investigated spatial knowledge acquisition during assisted pedestrian navigation through the real-world, using a route which included the one recorded for Experiment 2.

Based on previous studies, we expected a better performance for navigators receiving landmark-based navigation instructions, especially for landmarks at navigation relevant locations, irrespective of the navigated environment. This impact of landmark-based navigation instructions on incidental spatial knowledge acquisition was expected to be observable in clearly controlled experimental scenarios as well as realistic real world settings.

General Methods

Experiment Procedure

Each Experiment consisted of two parts and included a between-subjects design comparing participant groups receiving different auditory navigation instructions. The first part was an assisted navigation period where participants followed auditory navigation instructions to navigate along a predefined route. In the second part, participants had to solve different tasks testing spatial knowledge acquisition regarding the navigated environment. Participants were not informed prior to the second part that they will be tested on the navigated environment. Thus, it was assumed that the acquired spatial knowledge was learned incidentally during navigating. It was shown that landmark and route knowledge can be incidentally acquired during navigation to a similar level as intentional learning (van Asselen, Fritschy, & Postma, 2006).

Specific setup characteristics varied across the three experiments (see Table 1). From the first to the last experiment, the navigation environment changed from an artificial/static laboratory setup to a real-world setting. Due to the change in environmental control, some route characteristics changed with the paradigm shift from simulated driving to walking through an urban environment. Based on changes in speed from car driving to walking, the definition of navigation relevant intersections and landmarks was adapted. In the first experiment, replicating the previous driving scenario (Gramann et al., 2017; Wunderlich & Gramann, 2018), only landmarks at intersections with route direction changes were defined as navigation relevant. In the subsequent two experiments using a pedestrian scenario, all landmarks at intersections were defined as navigation relevant even when no direction change of the route was experienced. This was done because landmarks between route turns serve as confirmation and improve user confidence in/during pedestrian navigation assistance (May Ross, Bayer, & Tarkiainen, 2003; Rousell & Zipf, 2017). Navigation instructions were provided prior to all intersections with navigation relevant landmarks. In the modified navigation instruction conditions, these included information about the respective navigation relevant landmark. Navigation irrelevant landmarks were located in between navigation relevant landmarks and were not mentioned in navigation instructions.

In contrast to the first experiment, for the two experiments using a pedestrian scenario, navigation irrelevant landmarks were located alongside straight segments of the route without junctions, whereas in Experiment 1 navigation irrelevant landmarks were also located at intersections.

Various questionnaires about demographic data, current state, individual navigation, gaming, and learning habits, simulation sickness (SSQ, Kennedy, Lane, Berbaum, & Lilienthal, 1993), and spatial abilities were collected either at the beginning or end of the experimental sessions (see Table 1). For subjective ratings of navigation task-related mental load and of individual orienting ability, the NASA-RTLX (National Aeronautics and Space Administration - raw task load index, Hart, 2006; Hart, & Staveland, 1988) and the Santa Barbara Sense of Direction (SBSOD, Hegarty, Richardson, Montello, Lovelace & Subbiah, 2003) was used, respectively. The Perspective Taking/Spatial Orientation Test (PTSOT, Hegarty & Waller, 2004) and the reference frame proclivity test (RFPT, Gramann, Müller, Eick & Schönebeck, 2005; Goeke, Kornpetpanee, Köster, Fernándes-Revelles, Gramann, & König, 2015) were recorded as additional measures for participants' individual spatial abilities and preferences in a subset of the experiments.

Navigation instruction conditions

All experiments required participants to navigate from a start to an end location following the auditory navigation instructions. The navigation instructions were the only between subject factor so that participants experienced only one navigation instruction condition. Thus, it was assured that participants were unaware of the spatial tasks during navigation. The control group received standard navigation instructions as known from commercial navigation aids. In the first experiment, the standard instructions provided information about the distance of the upcoming intersection and the turning direction (e.g., "In 100 m, turn right at the next intersection.") replicating the instructions used in Wunderlich and Gramann (2018), while in Experiment 2 and 3, the instructions did not include precise distance information (e.g., "At the next intersection turn right."), similar to Gramann and colleagues (2017).

The two versions of modified navigation instructions used in Gramann et al. (2017) and Wunderlich and Gramann (2018) included both the name of a landmark at the intersection and an additional information. In one case this information was redundant, such as, "Turn right at the bookstore. There, you can buy books." In the other case, it included a reference to one of the participant's personal interests, like, "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. These personal-reference navigation instructions were individualized for each participant in the personal-reference condition.

By using only these two conditions, however, it was not possible to interpret the differences in spatial knowledge acquisition between the modified navigation instructions. One explanation for improved spatial knowledge acquisition could have been the personal-reference in the instruction. Alternatively, simply adding additional, more-detailed information might have led to the observed spatial learning effects. To overcome this limitation, we introduced an additional modified navigation instruction condition, the *long* condition. The long landmark-based navigation instructions referenced a landmark at each navigation relevant intersection and provided additional semantic information about this landmark. This detailed information contained more semantic information than the redundant description of the landmark in the contrast-modified navigation instruction used in the previous studies, but had no relation to the personal interests of the participants. Thus, there was no need to individualize the additional information and all participants of the long-modified condition heard the same navigation instructions (e.g. "Turn right at the bookstore. There, public readings take place every week.").

Because previous studies revealed comparable spatial recognition performance for different modified navigation instructions, it was hypothesized that a simple reference to a landmark might be sufficient to enhance incidental spatial learning. To test this assumption, a *short* modification of the navigation instructions was created containing only the landmark name with no additional information ("Turn right at the bookstore."). This condition was similar to the landmark-based navigation instructions in the usability study of Ross, May, & Thompson (2004). In summary, the first of the here reported experiments used standard and long landmark-based navigation instructions, while experiments 2 and 3 used standard as well as short and long landmark-based navigation instructions.

Cued-recall task

After the navigation phase and a subsequent break of varying length, the participants solved several spatial tasks. The present paper focuses on the cued-recall task which was used in all three experiments and also allowed for a comparison with the landmark recognition tasks used in the previous experiments. The cued recall task was similar to the landmark recognition task of Gramann et al. (2017) and Wunderlich & Gramann (2018). However, because the task combined a simple landmark recognition with a route direction response comparable to Huang and colleagues (2012), the term cued-recall task will be used for the remainder of this paper. In this task, a randomized set of landmark pictures was shown to the participant who had to decide whether each landmark had been part of the previously navigated route (landmark recognition representing the level of landmark knowledge) and how the route had proceeded at this location (route direction representing the level of route knowledge). The snapshots of the route and surrounding area were presented to the participants either via projection on a wall (Experiment 1) or on a desktop screen (Experiment 2 and 3). Participants had to respond according to the previously navigated route using either the steering wheel and pedals of the driving simulator setup, or the arrow keys of the keyboard in the pedestrian scenarios. In case the route had had turned right/left at the displayed landmark, they were instructed to steer to the right/left or press the right/left arrow key, in case it had proceeded straight to press the gas pedal or the up arrow key, or in case this landmark had not been present alongside the route to respond by pressing the brake pedal/down arrow key. The relative location of navigation relevant landmarks at intersections (left, right, before or after the intersection) did not provide any indication for the respective turning directions.

Landmarks were categorized according to their relevance for the navigation task: a) *navigation relevant landmarks* were referenced in the modified navigation instructions while b) *navigation irrelevant landmarks* were located at straight route segments and were not referenced in the modified navigation instructions. In addition, c) *novel landmarks* were presented, which were from the same environment, but were not encountered during the navigation phase. Within each experiment, all snapshots provided the same perspective and weather conditions and were presented in a randomized order with short breaks after every 30 presentations. In Experiment 2 and 3, following to the participants' responses, the participant was asked how confident s/he was about the given answer on a six-point scale ranging from '1 - very sure' to '6 - I did not know'.

In Wunderlich & Gramann (2018) and Experiment 2 of the present paper, all landmarks were presented more than once to reach a sufficient number of epochs per landmark type for the analyses of event-related brain activity associated with the presentation of landmark pictures. In this case the complete landmark set was repeated several times, with landmark pictures being shuffled randomly each time. Within the scope of the present paper, only the responses to the first presentation of the landmark pictures are reported as these represent the unbiased responses of participants. To allow for a direct comparison of the present results with the previous study by Wunderlich and Gramann (2018), unpublished data of the performance for the first presentation only from Wunderlich and Gramann (2018) are included in the discussion section.

Table 1: Overview of procedure characteristics for all reported experiments. All information beyond the scope of the here reported analysis is shown greyed out.

	Experiment	1	2	3
General	Total duration	Ca. 2.5 hours	Ca. 2.7 hours	Ca. 3.5 hours
	Collection of EEG data	No	Session 1 + 2	Session 2
	Eye-tracking	Session 1 + 2	Session 1 + 2	No
	Experimental setting	Laboratory	Laboratory	Session 1: Field Session 2: Lab
Navigation session	Environment	Simulated city	Video of real-world	Real-world
	Movement	Simulated driving	Interactive video	Walking
	Other traffic participants	One other car	Plenty, invariant across participants	Plenty, varying across participants
	Route details	- 55 junctions - 7 turns - 10 min	- 20 junctions - 14 turns - 35 min	- 40 junctions - 22 turns - 60 min
	Navigation instruction conditions	Standard Long	Standard Short Long	Standard Short Long
	Questionnaires pre-navigation	Demographic data Current state Gaming behavior Driving behavior SBSOD	Current state	Current state
	Questionnaires post-navigation	NASA-RTLX SSQ (3 Items) RFPT PTSOT	NASA-RTLX Route familiarity	NASA-RTLX Route familiarity
Break		18 to 24 days, $M = 21$ days, $SD = 1.34$ days	Short break of some minutes	13 to 17 days, $M = 26.6$ days, $SD = 3.03$ days
Spatial tasks session	Sketch Map	One before cued-recall task and one after re-drive	One as first task	None
	Cued-recall task details	- 21 pictures - Count down 3s - Picture until response - No confidence rating - One cycle	- 60 pictures - Fixation cross 1s - Picture for 3s - confidence rating - Three cycles	- 120 pictures - Fixation cross 1s - Picture until response - confidence rating - One cycle
	Further tasks	Scene ordering Unassisted re-drive	PTSOT Circle Task	Video-turn evaluation
	Questionnaires	NASA-RTLX SSQ (3 Items) Acceptance of the new technology	Demographic data SBSOD Learning type	Current state Demographic data SBSOD

Statistical analysis

Statistical analysis was performed using the statistics software SPSS (International Business Machines Corporation (IBM) Analytics, Armonk, USA). A mixed measures analysis of variance (ANOVA) was computed with the between-subject factor navigation instruction condition and the within-subject factor landmark type (relevant, irrelevant, novel). In Experiments 2 and 3, the between subject factor had three levels (standard, short, long) while in Experiment 1 the between subject factor had two levels (standard and long). In case of violation of the sphericity, the Greenhouse-Geisser corrected p-values and degrees of freedom were reported (Rasch, Friese, Hofmann & Naumann, 2010). As an indicator of the effect size, partial eta squared was calculated.

Experiment 1

To exclude any impact of additional visual instructions on spatial learning during navigation, the first Experiment tested whether the overlay of the previously used visual navigation cue might have caused the observed suppression of landmark learning at navigation relevant intersections. Previous studies investigating the impact of landmark-based navigation instructions on spatial knowledge acquisition used auditory navigation instructions alongside a visual navigation cue - a semi-transparent hologram arrow projected in the virtual environment directing the route direction (see Figure 1b; Gramann et al., 2017; Wunderlich & Gramann, 2018).

Method

Participants. The first Experiment comprised 29 participants (13 females) with gender balanced across experimental conditions (standard navigation instruction with 16 participants, 7 female; long navigation instruction with 13 participants, 6 female). The age ranged between 22 and 53 years (M = 31.7 years, SD = 6.29 years). Participants were recruited through an existing database or personal contact, and were reimbursed (8 Euro per hour) or received course credit. Participants were required to have had a drivers' license for two years or more and to have driven at least 1000 km per year to assure a basic driving experience. All had normal or corrected to normal vision, and gave informed consent prior to the study. The study was approved by the local ethics committee.

Procedure. The Experiment took place in the same driving simulator and laboratory setup (Figure 1a) as the study by Wunderlich & Gramann (2018). The time period between the navigation session and the spatial tests was again three-weeks. Only slight changes were made regarding the technical setup of the driving simulator to allow for turning the steering wheel 360 degrees from neutral position in both directions in the new setup (previously restricted to 110 degrees). In contrast to the previous studies, the visual turning indicator (Figure 1b) was replaced by a second auditory turning instruction (e.g. "Now turn right.") played when reaching the respective intersection. The second navigation instruction was presented at all intersections and was identical for all navigation instruction conditions. This way, the potential impact of a visually augmented turning instruction in previous studies was addressed. The identical virtual world and route introduced by Gramann and colleagues (2017) was used on two groups of participants receiving either a standard or long landmark-based navigation instructions. Compared to the spatial task order of Wunderlich and Gramann (2018), the cued-recall task took place after the first sketch map drawing task. All other task characteristics were kept constant including the definition that any turn of the steering wheel was considered a correct response to navigation relevant landmarks irrespective of the actual route direction. Further small changes in the paradigm contained the use of additional questionnaires as listed in Table 1 their results are not reported here.

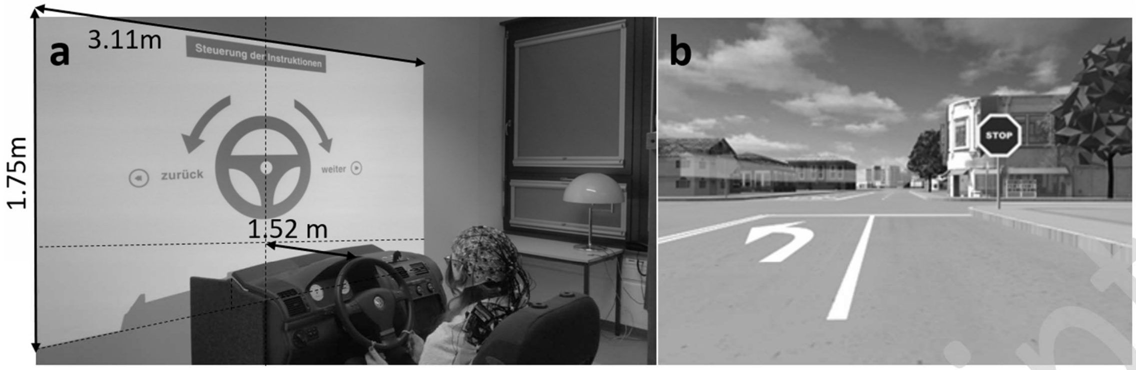

Figure 1: a) Driving simulator setup and b) the previously used hologram arrow projected into the virtual environment (Figure adapted from Wunderlich & Gramann, 2018).

Results

The mixed measures ANOVA with the between-subject factor navigation instruction condition (standard, long) and the repeated measures factor landmark type (relevant, irrelevant, novel) revealed a significant main effect of navigation instruction condition ($F_{(1,27)} = 11.38$, $p = .002$, $\eta_p^2 = .296$) and a main effect of landmark type ($F_{(2,54)} = 3.59$, $p = .034$, $\eta_p^2 = .117$). The interaction of both factors showed a trend towards significance ($F_{(2,54)} = 3.10$, $p = .053$, $\eta_p^2 = .103$). Bonferroni-corrected post-hoc comparisons revealed a trend towards significance in the cued-recall performance between relevant landmarks ($M = 56.1$, $SE = 3.48$) and irrelevant landmarks ($M = 67.5$, $SE = 3.83$, $p = .082$), whereas other comparisons showed comparable performance (all ps > .112). The post hoc comparisons of the interaction term revealed that the cued-recall performance for relevant landmarks of navigators receiving standard instructions ($M = 42.0$, $SE = 4.66$) was significantly lower than their recognition performance for irrelevant landmarks ($M = 67.0$, $SE = 5.13$, $p < .001$). In addition, for relevant landmarks, standard instructions were associated with significantly lower cued-recall performance compared to modified navigation instructions ($M = 70.3$, $SE = 5.16$, $p = .002$). All other post hoc comparisons did not reach significance (all ps > .160). The group-boxplots and individual measures can be seen in Figure 2.

Discussion

Experiment 1 aimed at investigating whether the previously used visual turn indicator partially overlapping with the environment at navigation relevant intersections fostered a suppression of spatial learning in the standard navigation instruction condition. To this end, the former setup was replicated while replacing the visual navigation instruction with a second auditory turn instruction. Furthermore, the long landmark-based navigation instruction combining the landmark name and additional detailed information about the respective landmark with the turning direction was introduced.

The results of Experiment 1 showed a better cued-recall performance for the long-modified navigation instruction condition as compared to standard instructions replicating an improved spatial knowledge about the navigated environment when using landmark-based auditory navigation instructions. The lowest percentage of recognized landmarks was observed in the standard navigation instruction condition when responding to navigation relevant landmark pictures. This replicated the results of earlier studies (Gramann et al., 2017, Wunderlich & Gramann, 2018) and confirmed the hypotheses a) that standard navigation instructions suppress incidental spatial learning at navigation relevant intersections and b) landmark-based navigation instructions are a way to overcome this

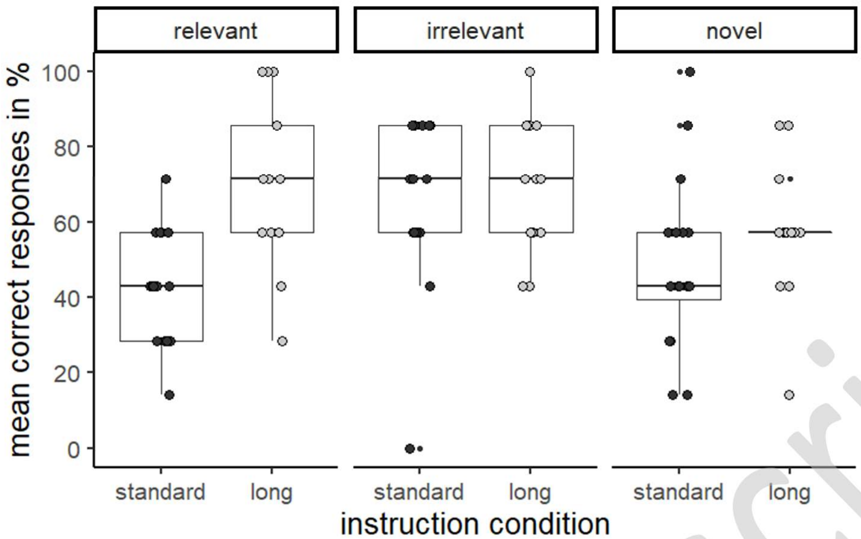

Figure 2: Boxplots and single subject performance scores in the first repetition of the cued-recall task of Experiment 1 using a driving simulator setup and seven landmarks in each category (relevant, irrelevant, novel). As 100% equals the correct response to seven landmarks of the respective category, the performance measure could take on seven different values with a step-width of 100/7 %. Whiskers display values up to 1.5 standard deviations (SDs) from the mean. Small dots represent individual values above the whiskers.

suppression. It can thus be concluded that the visual turn indicator was not the cause for the previously observed spatial learning suppression effect. In the present study, no visual navigation instruction was presented that might have suppressed information processing of environmental features at navigation relevant intersections. Still, navigators receiving standard navigation instructions revealed a significantly lower cued-recall performance for navigation relevant landmarks. The suppression of landmark learning must thus be related to differences in the navigation instruction itself.

As there were only minor changes to the setup, a direct comparison of the performance results with the data of Wunderlich and Gramann (2018) is possible. In Figure 3, the performance results are presented alongside the recognition performance for the first landmark presentation from the study by Wunderlich and Gramann (2018). Both experiments had a break of three weeks between the navigation phase and the cued-recall test. The performance of both standard navigation instruction conditions is on a comparable level in all landmark categories indicating the reliability of the navigation instruction effects. Participants using the long navigation instructions revealed a comparable cued-recall performance as participants using modified navigation instructions with references to personal interests. The comparable recognition performance for long and personal-reference instructions supports the assumption that improved spatial knowledge acquisition through modified navigation instructions is based on additional semantic information related to navigation relevant landmarks and not to the personal reference. Thus, it might be argued that mentioning a favorite thing, as done in the previous studies, may not be sufficient to trigger the personal-reference effect (for a review see Symons and Johnson,1997).

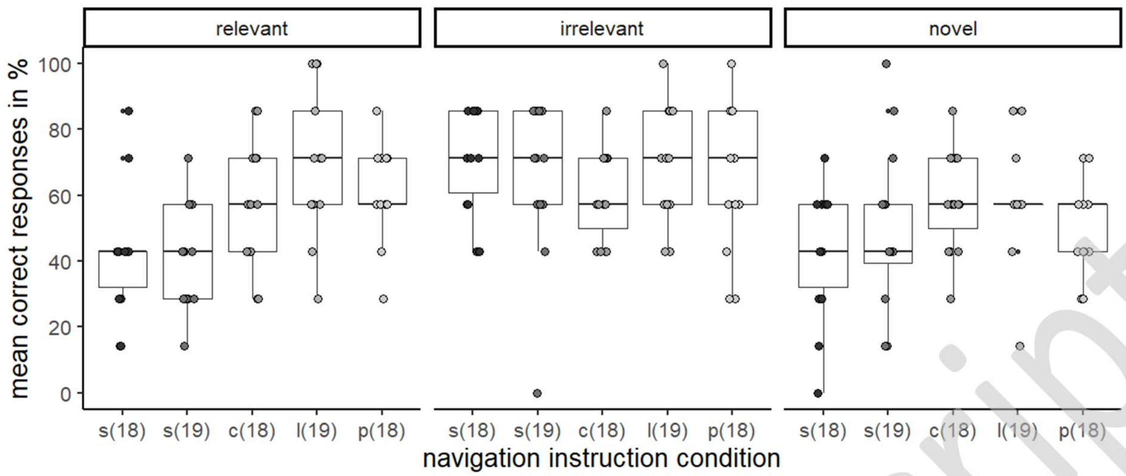

Figure 3: Boxplots and single subject performance scores in the first repetition of the cued-recall task of Wunderlich & Gramann (2018, abbreviated as 18) and of Experiment 1 (abbreviated as 19) using a driving simulator setup and seven landmarks per landmark category. Navigation instruction conditions are indicated by abbreviations with s = standard instructions, c = contrast modified instructions, l = long-modified instructions, p = personal-reference instructions. As 100% equals the correct response to seven landmarks of the respective category, the performance measure could only attain seven different values with a step-width of 100/7 %. Whiskers display up to 1.5 standard deviations (SDs) from mean and small dots represent individual values above.

As the results showed that the long landmark-based navigation instructions were associated with comparable landmark learning effects as the personal-reference condition, this modification was chosen for further investigations. Beneficially, this reduces concerns regarding data security and the requirement to collect personal information before the navigation phase. Furthermore, as improved incidental spatial learning was based on the modified auditory navigation instructions and not related to the visual navigation indicator, the applicability of this simple, but promising modification of navigation assistance systems was investigated in more realistic settings.

Experiment 2

After replicating the incidental spatial learning effect without visual navigation cues, the modified navigation instruction approach was tested in a more realistic environment providing real-world visuals during navigation. To this end, an interactive video from the first-person perspective of a pedestrian during real-world navigation through an urban environment was created.

Method

Participants. Forty-four participants took part in this experiment, including twenty-two women (15 participants in the standard instruction condition, 15 in the short instruction condition, and 14 in the long instruction condition). Gender was balanced across experimental conditions. The age ranged from 19 to 34 years (M = 26.1 years, SD = 2.72 years). Participants were recruited through an existing database or personal contact and were reimbursed (10 Euro per hour for electroencephalographic (EEG) recordings) or received course credit. To assure that participants were not familiar with the route in the navigation task, they were asked to rank up to five metro stations of Berlin according to their frequency of personal use in an online questionnaire prior to the experiment. If one of the stations was close to the route, the participant was excluded from the experiment. All participants had normal or corrected to normal vision and gave informed consent prior to the study. The study was approved by the local ethics committee.

Procedure. During the experiment, participants saw the interactive video and listened to different navigation instructions. The task was interactive in the sense that the video stopped at intersections and participants had to respond according to the previous navigation instruction otherwise the video would not commence again. In a cued-recall task after the navigation phase, they had to respond whether a displayed landmark was experienced before and if so, which direction the route took at the respective intersection.

The Experiment took place in a controlled laboratory environment (Figure 4a) with participants sitting in front of a display and responding using the keypad in front of them. Participants were equipped with 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 4: a) Interactive video setup of Experiment 2. The screen in front of the participant was displaying the video and was equipped with the eye-tracker, a second screen was for EEG-data and the laptop for eye-tracking data collection. b) Video snapshot at a navigation relevant landmark ("public restroom") as used in the cued-recall task (pictures were presented in color).

The video content was recorded with a GoPro Hero 4 (GoPro. Inc., San Mateo, USA) from a pedestrians' perspective (see Figure 4b) with the cameraperson continuously recording while walking a predefined route. The movie contained vertical movements accompanying each step and conveyed the feeling of pedestrian movement to participants. The navigation task showed a 3.7 km long route through Charlottenburg, Berlin in Germany, with twenty intersections containing 14 direction changes. The video was accelerated 1.1 times the original speed to shorten the navigation task to approximately 35 min. Auditory navigation instructions providing standard or landmark-based information were given prior to each intersection. When arriving at an intersection, the movie would stop and participants had to respond according to the instructed direction by pressing the respective key. Walking directions were indicated by using the left (turn left), up (go straight), or right (turn right) arrow key. This interaction was implemented to ensure the participants' attention to the route. Irrespective of the correctness of the navigation direction response, the response key started the video again. The stimulus material was identical for all participants and only the navigation instructions differed between the groups. Beside the standard navigation instructions, the short and long landmark-based navigation instructions were tested. During the video, various other pedestrians, cars and other road users were visible. The street noise was turned off to include visual realism only and navigation instructions were presented via loudspeakers. In the pedestrian experiments, navigation instructions were provided before every intersection and no second turning direction instruction was needed as participants were able to identify the relevant intersection easily.

The navigation phase was directly followed by a sketch map drawing task and the cued-recall task (as in Gramann et al., 2017). Because the navigated route contained twenty intersections, twenty landmark pictures of each landmark type were used (navigation relevant = at intersections, navigation irrelevant = between intersections, novel = at or in between intersections, but not alongside the route). Pictures of relevant and irrelevant landmarks were screenshot from the video and presented from the pedestrians' point of view including the direct surroundings and the novel landmarks were screenshots of landmarks taken from parts of the navigation video that were not shown to participants. Every landmark picture was displayed for 3 s and then replaced by a Figure showing the four response keys. Overall, sixty landmarks were presented three-times each, randomized within each of the three blocks whereas only the first presentation was analyzed for the presented results.

Results

The mixed measures ANOVA with the between-subject factor navigation instruction condition (standard, short, long) and the repeated measures factor landmark type (relevant, irrelevant, novel) revealed a significant main effect of navigation instruction condition ($F_{(2,41)} = 4.31$, $p = .020$, $\eta_p^2 = .174$) and a main effect of landmark type ($F_{(2,82)} = 20.0$, $p < .001$, $\eta_p^2 = .328$). The interaction of both showed a trend towards significance ($F_{(4,82)} = 2.36$, $p = .060$, $\eta_p^2 = .103$).

One post-hoc comparison using Bonferroni correction revealed differences in cued-recall performance between the three navigation instructions: The performance in the long-modified navigation instruction was higher ($M = 71.2$, $SE = 2.26$) than the performance in the short-modified condition ($M = 62.3$, $SE = 2.34$, $p = .029$). The difference between long and standard instructions ($M = 63.9$, $SE = 2.26$) showed a trend towards significance ($p = .081$). The overall performance of standard and short was statistically indissociable ($p > .999$). Regarding the landmark types, the post-hoc comparisons revealed that the cued-recall performance was lower for navigation relevant ($M = 55.0$, $SE = 2.10$) compared to navigation irrelevant ($M = 73.6$, $SE = 2.06$, $p < .001$) and novel landmarks ($M = 68.9$, $SE = 2.45$, $p < .001$). Novel and irrelevant landmarks revealed comparable recognition performance ($p = .493$).

Contrasting the performance differences for navigation relevant landmarks of the different navigation instruction conditions revealed that long instructions ($M = 65.0$, $SE = 3.59$) outperformed standard instructions ($M = 45.7$, $SE = 3.59$, $p = .001$), but not short navigation instructions ($M = 54.3$, $SE = 3.72$, $p = .134$). Comparing the landmark types only for the standard navigation instruction condition revealed significantly lower performance values for relevant ($M = 45.7$, $SE = 3.59$) compared to irrelevant ($M = 76.7$, $SE = 3.53$, $p < .001$) and novel landmarks ($M = 69.3$, $SE = 4.19$, $p < .001$). In the short navigation instruction condition, performance values for relevant landmarks ($M = 54.3$, $SE = 3.72$) was significantly lower than for irrelevant landmarks ($M = 68.6$, $SE = 3.65$, $p = .010$). When contrasting landmark types in the long navigation instruction condition the lower performance values for relevant ($M = 65.0$, $SE = 3.59$) compared to irrelevant ($M = 75.7$, $SE = 3.53$, $p = .061$) showed a trend towards significance. All other post-hoc contrasts had p-Values above .256. The group-boxplots and individual measures can be seen in Figure 5.

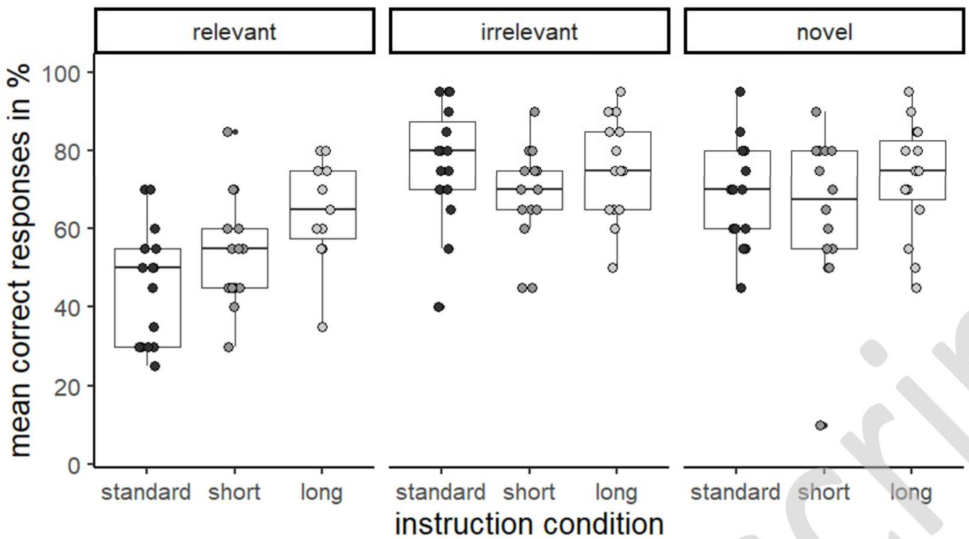

Figure 5: Boxplots and single subject performance scores in the first repetition of the cued-recall task of Experiment 2 using an interactive video with twenty landmarks per landmark category (relevant, irrelevant, novel). As 100% equals the correct response to twenty landmarks of the respective category, the performance measure could only attain twenty different values with a step-width of 5%. Whiskers display up to 1.5 standard deviations (SDs) from mean and small dots represent individual values above the whiskers.

Discussion

In Experiment 2, a paradigm shift from simulated driving to video-based pedestrian navigation was realized testing the incidental spatial learning effect in a more realistic setting. Two different landmark-based navigation instructions (short and long) were compared with a control group.

Descriptively, the performance data for all subgroups of the 3x3 design was in the same range as the performance data of Experiment 1, despite the setup change from simulated driving to an interactive video showing real-world visuals from a pedestrian perspective including other traffic participants. This is remarkable and reveals that the processes leading to incidental spatial learning seem to be of a more general nature and setup-independent. The cued-recall performance pattern again supports the assumption that a) incidental spatial learning at navigation relevant intersections was suppressed by standard navigation instructions but b) enhanced by landmark-based navigation instructions. This strengthened the reliability and generalizability of this effect as it was also observed in a more realistic environment and using a different movement mode.

Like Experiment 1, the results of Experiment 2 revealed two significant main effects and a marginally significant interaction replicating the positive impact of modified navigation instructions on spatial learning during navigation. The post-hoc comparisons of the main effect for the factor navigation instruction showed a better performance for the long as compared to the short navigation instruction condition across all landmark types but no difference between the short navigation instruction and the standard instructions. This result was unexpected as we had assumed that landmark recognition for short navigation instructions would be better than for standard instructions but equal or worse compared to long navigation instructions. The results, thus, point to a difference between the landmark-based modifications of navigation instructions revealing that a simple and short reference to a landmark might be less effective with regards to incidental spatial learning. The results support the assumption that additional detailed landmark information included in navigation instructions foster incidental spatial learning. However, the absence of a statistical difference between the standard instructions and the long navigation instruction condition in the post-hoc comparisons of the main effect curtails this conclusion to a certain degree and can only be explained by the very good performance regarding navigation irrelevant landmarks of participants in the standard navigation instruction condition. This phenomenon had been found before and is possibly driven by a response bias for the decision that a landmark "was alongside the route" in case of doubts (Wunderlich & Gramann, 2018).

Regarding the factor landmark type, all participants irrespective the navigation instruction condition acquired the least spatial knowledge about landmarks at navigation relevant intersections. This points towards a possible shift of attention during more difficult navigation phases when passing an intersection, reducing the amount of attention available for processing the environment. It further confirms the assumption that landmark-based navigation instructions overcome the incidental spatial learning suppression instead of leading to additional learning. However, the post-hoc comparisons of the marginal interaction effect revealed the hypothesized order for the different navigation instruction conditions with the best recognition performance for long instructions, followed by short and standard instructions. The difference in cued-recall performance between relevant as compared to irrelevant and novel landmarks decreased accordingly, revealing less suppression when landmark-based navigation instructions are used.

Using a video-based navigation paradigm still lacks the natural movement and the accompanying kinesthetic and proprioceptive information. To allow multimodal information integration of all senses involved in natural navigation through the real world, Experiment 3 implemented a real-world navigation task with pedestrians actively navigating through the same area in Berlin that was displayed in the video of Experiment 2.

Experiment 3

The third Experiment aimed at testing the ecological validity of the previously demonstrated incidental spatial learning effects during the use of modified navigation instructions in an unrestricted, real-life setting.

Method

Participants. In this experiment, 36 participants were recorded (21 females) aged between 20 and 34 years ($M = 26.6$ years, $SD = 3.03$ years). Every experimental condition consisted of twelve participants and gender was balanced across conditions (standard instructions: 8 female, short instructions: 6 female, long instructions: 7 female participants). Participants were recruited through an existing database or personal contact and were reimbursed (8 or 10 Euro per hour for performance data only and for EEG recordings, respectively) or received course credit. All had normal or corrected to normal vision and gave informed consent prior to the study. The study was approved by the local ethics committee.

Procedure. Participants navigated along a predefined route through an urban environment, the district of Charlottenburg, Berlin in Germany. The route was longer and comprised the identical route segment that was presented in the video in Experiment 2. In addition, a route segment before and after the segment presented in the video were included. Three groups of participants were guided by auditory navigation instructions either receiving long or short landmark-based navigation instructions while a control group received the standard navigation instructions without landmark information. After a break of two-weeks, participants had to solve the cued-recall task in a laboratory setting.

In the first session of Experiment 3, an experimenter met participants at a train station close to the starting point of the route. Participants were informed about the upcoming navigation task and 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 in which direction to go. While navigating the route, an experimenter was walking in the immediate vicinity of the participant to intervene in case of hazards and ensure that the participant would follow the correct route (see Figure 6a). The experimenter also manually triggered the auditory navigation instructions using a browser-based application on a mobile phone. The auditory navigation instructions were provided to both the participant and the experimenter via Bluetooth headphones (Cheetah Sport In-Ear, Mpow, Hong Kong, China) at predefined trigger points alongside the route. After a navigation phase of approximately 60 min including 40 intersections, participants arrived at the end of the route.

In the spatial task session following after a break of 2 weeks, participants were equipped with EEG (BrainAmps, Brain Products, Gilching, Germany) and seated at a table in front of a computer screen and keyboard in a controlled laboratory setting. Analogous to the cued-recall task of Experiment 2, forty landmark pictures of each landmark type were shown. Again, pictures of landmarks included also their surroundings, but displayed a front view of the landmark that deviated from the pedestrian view (see Figure 6b compared to Figure 4b). Novel landmarks 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 an arrow key. In total, 120 landmark pictures were presented once.

Figure 6 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).

Results

The mixed measures ANOVA with the between-subject factor navigation instruction condition (standard, short, long) and the repeated measures factor landmark type (relevant, irrelevant, novel) revealed a significant main effect of navigation instruction condition ($F_{(1,33)} = 3.39$, $p = .036$, $\eta_p^2 = .183$) and a main effect of landmark type ($F_{(1.26,41.7)} = 57.4$, $p < .001$, $\eta_p^2 = .635$). The interaction of both factors did not reach significance ($F_{(2.53,41.7)} = 1.72$, $p = .184$, $\eta_p^2 = .095$).

The post-hoc comparisons for the navigation instruction conditions displayed only trends towards significance when comparing standard ($M = 40.2$, $SE = 2.75$) and short ($M = 49.0$, $SE = 2.75$, $p = .090$) as well as standard and long ($M = 49.7$, $SE = 2.75$, $p = .062$). The post hoc comparisons of the landmark type revealed that the performance for relevant landmarks ($M = 40.6$, $SE = 1.99$) was significantly higher than for irrelevant landmarks ($M = 28.0$, $SE = 2.98$, $p < .001$) and significantly lower than the recognition performance for novel landmarks (*M* = 70.3, *SE* = 3.35, *p* < .001). Additionally, the novel landmarks were significantly more often correctly recognized than irrelevant landmarks (*p* < .001).

The cued-recall performance for relevant landmarks was significantly lower in the standard navigation instruction condition (*M* = 30.4, *SE* = 3.44) compared to the short (*M* = 42.7, *SE* = 3.44, *p* = .049) and the long instruction condition (*M* = 48.5, *SE* = 3.44, *p* = .002). Considering the landmark types within the standard navigation instruction condition, post-hoc comparisons revealed a significantly higher performance for novel (*M* = 60.8, *SE* = 5.81) as compared to relevant (*M* = 30.4, *SE* = 3.44, *p* < .001) and irrelevant landmarks (*M* = 29.38, *SE* = 5.16, *p* = .005). Relevant and irrelevant landmarks were statistically indifferent (*p* > .999). In the short navigation instruction condition, cued-recall performance for relevant landmarks (*M* = 42.7, *SE* = 3.44) was significantly higher than for irrelevant (*M* = 25.8, *SE* = 5.16, *p* = .003) and significantly lower than for novel landmarks (*M* = 78.5, *SE* = 5.81, *p* < .001). The difference between irrelevant and novel landmarks was also significant (*p* < .001). When contrasting the long navigation instruction condition the performance values for relevant landmarks (*M* = 48.5, *SE* = 3.44) were significantly higher compared to irrelevant landmarks (*M* = 28.8, *SE* = 5.15, *p* = .001) and significantly lower than for novel landmarks (*M* = 71.7, *SE* = 5.81, *p* = .003). Again, the difference between irrelevant and novel landmarks was significant (*p* < .001). The group-boxplots and individual measures can be seen in Figure 7.

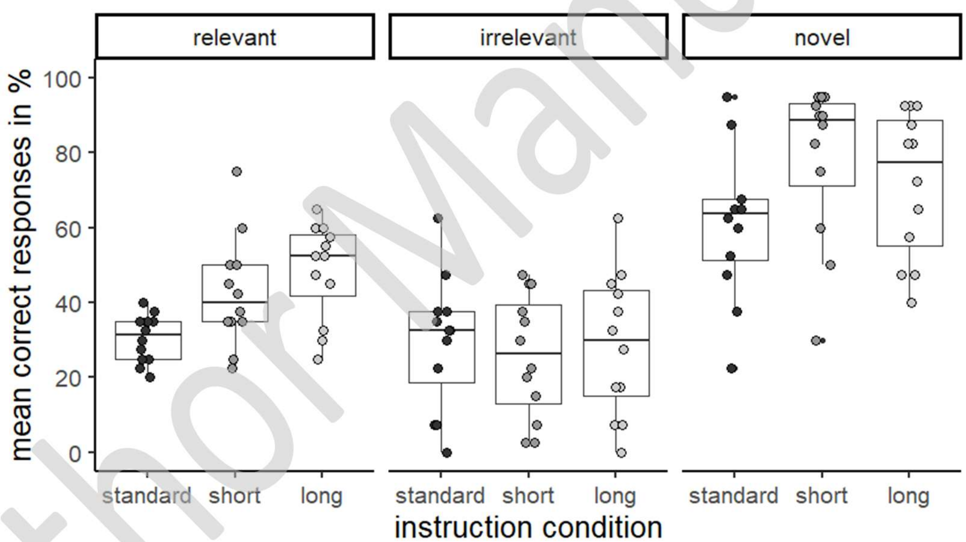

Figure 7: Boxplots and single subject performance scores in the first repetition of the cued-recall task of Experiment 3 taking place in real-world using forty landmarks per landmark category. Whiskers display up to 1.5 standard deviations (SDs) from mean and small dots represent individual values above the whiskers.

Discussion

Experiment 3 tested incidental spatial learning during assisted navigation when walking in an uncontrolled real-world setting with a dynamically changing environment including cars and other pedestrians. The results of the cued-recall task again showed the same effect of navigation instruction condition revealing an improved cued-recall performance when navigating with landmark-based navigation instructions. The significant difference between short and long navigation instructions as observed in Experiment 2, however, was not replicated. Also, the results regarding cued-recall of different landmark categories revealed a different pattern than the previous experiments. For the first time, navigation irrelevant landmarks alongside the route revealed significantly lower recognition performance than navigation relevant landmarks irrespective of the navigation instruction condition. The recognition performance for novel landmarks was again relatively high, as observed in previous experiments.

The surprisingly lower recognition performance for navigation irrelevant landmarks in all navigation instruction conditions might have been caused by the characteristics of the specific experimental protocol. One possible explanation for this drop in performance for navigation irrelevant landmarks might have been the change of the perspective of the landmark pictures in the cued-recall task. In contrast to the previous experiments, landmark pictures were presented from a frontal view instead of the navigators' perspective. This might have been detrimental to the recognition of landmarks positioned along the route (navigation irrelevant) as participants turned their heads less during straight segments of the route compared to intersections. Thus, irrelevant landmarks were less likely encountered from such a frontal perspective.

Regardless of this difference in recognition performance for irrelevant landmarks, however, we again observed improved cued-recall performance for relevant landmarks when using landmark-based as compared to standard navigation instructions. This result replicates the spatial learning suppression when using standard instructions as observed in all previous experiments. In Experiment 3, the reduced learning suppression at navigation relevant intersections was most reflected in the performance differences for relevant landmarks compared to irrelevant landmarks. Whereas the recognition performance for landmarks alongside straight segments remained low, the performance for relevant landmarks increased significantly when using landmark-based instructions. This supports the assumption of a negative impact of standard navigation instructions on spatial knowledge acquisition and the alleviation of such a suppression effect by including landmark-based information in auditory navigation instructions.

General Discussion

The focus of this research was to investigate a potential spatial learning suppression accompanying established navigation instructions as well as enhanced incidental spatial knowledge acquisition when using landmark-based navigation instructions and whether both can be generalized to ecologically valid scenarios. To that end, three consecutive 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. Experiment 1 was testing the impact of visual navigation instructions on the suppression of incidental spatial learning during simulated driving. The other two experiments were testing landmark-based navigation instructions in more realistic environments including videos of (Experiment 2) as well as real-world pedestrian navigation (Experiment 3) through an unknown city area.

The results of all three experiments replicated the positive impact of the use of landmark information during navigation on spatial learning (Dey, Karahalios, & Fu, 2018; Goodman, Brewster, & Gray, 2005; Li, Fuest, & Schwering, 2014; Löwen, Krukar, Schwering, 2019; Tom and Denis, 2003, 2004). Furthermore, they replicated the findings from Gramann et al. (2017) and Wunderlich and Gramann (2018) demonstrating an increased cued-recall performance for landmark-based navigation instructions especially regarding navigation relevant landmarks. This underpins the robustness and the validity of the incidental spatial learning effect when using landmark-based auditory navigation instructions.

Following the argument that the spatial memory impairment during use of navigation aids is likely to be caused by divided attention between the movement and the navigation assistant (Gardony et al. 2013, 2015), spatial knowledge acquisition was expected to be impaired irrespective of the landmark category. In the studies of Gardony and colleagues only the retrieval of landmarks at decision points was investigated. The present results revealed a specifically impaired spatial knowledge acquisition for navigation relevant landmarks when using standard navigation instructions. This might be because standard navigation instructions bias the attention towards the intersection whereas landmark-based navigation instructions help to process environmental features and thus do not suppress incidental spatial learning. When instructing navigators to turn “at the next intersection” (Experiment 2 and 3) or “in 100 meters” (Experiment 1), attention is drawn to the intersection itself in order to identify the upcoming navigation-relevant intersection. Instead, the landmark cue in the modified navigation instruction draws the attention towards the surroundings of the street. This triggers the user to process the visual information at this navigation relevant location that may help to differentiate this place from other places and thus eases the successful learning of this information.

The results further provided first evidence that long landmark-based instructions lead to a comparable level of landmark learning as landmark-based instructions that include personal-references. This is an important finding as it allows to standardize navigation instructions for different users without requiring individualized modifications. The long landmark-based instructions do not necessitate the use of personal information which would otherwise be associated with data security concerns. The results from the reported experiments demonstrate that it would be sufficient to access publicly available information and then generate the landmark-based navigation instructions. This was already done for the inclusion of landmark names in navigation instruction by Dräger and Koller (2012) or Rousell and Zipf (2017). But the current results emphasize that besides including the landmark name adding general, current, and detailed information about this landmark would be of advantage for the incidental spatial learning. In Experiment 2, the benefit of the additional semantic information became visible as participants using more detailed landmark-based navigation instructions outperformed those following instructions containing the landmark name only.

The higher recognition performance of the control group for irrelevant and novel landmarks compared to relevant landmarks in Experiment 1 and 2 replicated previous studies (Gramann et al., 2017; Wunderlich & Gramann, 2018). This lends support to the assumption that standard navigation instructions suppress spatial knowledge acquisition at navigation relevant decision points. Modified navigation instructions instead seem to reverse the suppression effect by making features of the environment more salient. This augmentation allows to encode a specific landmark in association with a navigation relevant decision. Thus, spatial knowledge acquisition increases even though it seems not to lead to a higher cued-recall performance for relevant compared to irrelevant and novel landmark recognition. This combination speaks for a suppression of incidental spatial learning by standard instructions that is abolished with an increasing amount of landmark-related information in the auditory navigation instructions.

The special case of the cued-recall performance pattern based on the three landmark categories in Experiment 3 does not contradict the suppression hypothesis as the performance for novel landmarks remained high across navigation instruction conditions. The generally low recognition results for navigation irrelevant landmarks rather raised the question whether the objects that served as irrelevant landmarks were indeed recognized during the cued-recall task in all experiments. As the change of perspective in the landmark pictures from a first-person perspective while walking to a frontal perspective in the cued-recall task required the recognition of a perspective-independent memory of the landmark and not just the familiarity with the street scene. Thus, it is possible that the recognition was based on the street view and many features of the environment in the vicinity of the irrelevant landmark instead of the landmark itself. This argument could be applied the same way to navigation relevant and novel landmarks but the data showed no impact of the changed perspective on the recognition performance for these landmark types. To further understand what kind of spatial knowledge is acquired during assisted navigation, future experiments will need to systematically manipulate the picture perspective and/or content in the cued-recall task. For example, using another cued-recall task where the landmark surroundings were removed completely from the pictures would reveal more insights into the acquired landmark knowledge.

As the cued-recall task is a combination of landmark recognition and route direction recall, the navigation relevant landmarks were more difficult as they required route information retrieval besides the simple recognition of the landmark. In contrast, for navigation irrelevant and novel landmarks, recognition of the landmark itself was already enough and required no recall of further route information. In the virtual environment experiments, this was considered in the analysis by joining both turning responses as correct. With the interactive video setup and reframing of navigation relevant intersections in Experiments 2 and 3, this reduction of left/right/straight responses to one response category was no longer a suitable solution as three of the four possible responses would fall into the correct category. Thus, the likelihood of being correct by chance would amount to 75%. For the present paper, we thus counted only those responses that exactly indicated the route direction at the respective intersection, without adjusting for task difficulty. With this more conservative approach, the recognition performance for relevant landmarks in the pedestrian experiments was still in a similar range compared to the joint results in the simulated driving experiments demonstrating that the realism of the environment enhanced the precision of the acquired spatial knowledge.

Not yet considered within the scope of this series of experiments were commercial navigation aids using street names instead of “at the next intersection”. However, based on the reported results by Tom and Denis (2003, 2004), we would expect a suppression of spatial learning comparable to the standard navigation instructions used in the here reported experiments. Providing street names in the auditory navigation instructions is likely to draw the attention of the user to very specific locations in the environment, where a sign with a street name is expected (Ross, May, & Thompson, 2004). Thus, actual processing of environmental features is not fostered. Furthermore, most street names are abstract features and rarely have a connection to the streetscape, which makes them less helpful for recognizing streets or navigated routes.

An interpretation of the reported results is restricted to the specific scenario of incidental spatial learning after navigating one unknown route in an unfamiliar environment. 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 possible. Furthermore, the cued-recall performance allows conclusion about acquired landmark and route level knowledge, but not survey knowledge. Yet, this series of experiments covers both the transfer from low to high realism in the environment including visuals and other traffic participants as well as the realism of the movement dimension. Despite the setup changes, the incidental spatial learning effects were replicated. Furthermore, the described experiments overcame limitations of previous work including a potential impact of visual turn indicators or the unknown origin of spatial learning improvement when using personal-reference modified navigation instructions. Based on the results we can conclude that the visual instructions did not cause a suppression of spatial learning at navigation relevant intersections. The results further indicate that landmark-based navigation instructions using additional detailed information about the landmark work as well but are more practical than personalized navigation instructions while showing improved spatial knowledge acquisition over less informative landmark-based navigation instructions.

Conclusions

The findings of the present experimental series replicated the previously described incidental spatial learning improvements when using landmark-based navigation instructions. This effect was shown to be generalizable across different settings and types of movement. Thus, landmark-based navigation instructions are a promising tool to prevent deskilling of spatial abilities that comes with the use of standard navigation assistance systems. Especially the landmark reference combined with more detailed information prevailed amongst all tested modifications of auditory navigation instructions rendering this approach the most promising.

Future research should address the multiple use of landmark-based navigation instructions and the accompanying spatial knowledge acquisition. Using landmark-based navigation assistance combining landmark-based auditory navigation instructions with visual or other sensory augmentation might be able to further improve multimodal spatial learning that trains the user's orientation abilities enabling her to autonomously navigate the environment in the future.

Data Availability

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

Key points

- Standard navigation instruction lead to a suppression of spatial knowledge acquisition at navigation relevant intersections
- Landmark-based navigation instructions are able to reverse this suppression effect
- This incidental spatial learning effect was tested in three different experimental setups and was shown to be robust and ecological valid

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