Navigating Indoor with Maps: Representations and Processes

Andrew Battles and Wai-Tat Fu (wfu@illinois.edu)
Beckman Institute of Science and Technology, 405 N. Mathews Avenue
University of Illinois at Urbana-Champaign
Urbana, IL 61801 USA

Abstract

Novice participants were given a schematic map of a multi-level building and performed a series of wayfinding tasks. Consistent with previous research, we found a mix of wayfinding strategies adopted by participants. Further analysis showed that participants incrementally developed and used mental representations of the building by integrating perceptual cues and memories of visited locations with salient features and landmarks represented on the schematic maps. The formation and use of mental representations was found to correlate with spatial ability – participants with better spatial ability would more likely use mental representation to infer relative locations of landmarks and to derive directional guidance for navigation. As a result, the routes chosen were better than those who predominately rely on deictic references to the schematic maps and environment cues.

Keywords: Wayfinding; indoor navigation; mental representation of space; navigation strategies.

Introduction

With the increasing popularity of tablet computers and smartphones, having a map while navigating indoor is becoming common. In fact, schematic maps of many large buildings (e.g., shopping malls, airports, or hospitals) are available online, such that people can access them on their mobile devices while navigating inside the building. Previous research on wayfinding has studied how people perform prospective route planning with a map and situated route planning without a map (e.g., Holscher, et al., 2006; 2011; Tenbrink, et al., 2011). However, there is still a lack of research on how mobile schematic maps are used for situated route planning during indoor navigation. The goal of this paper is to explore indoor wayfinding strategies by novices as they navigate in a novel multi-level building using a schematic map of the environment. In particular, the current study focuses on how spatial ability impacts the use of deictic strategies and mental representations of space as novices perform wayfinding tasks indoor.

Wayfinding research

Much evidence shows that humans mentally represent the structure of an environment as a network graph with weighted connections (Kuipers, 1978; 200; Meilinger, 2008; Werner et al., 2000). However, there is also evidence that humans can adopt direction-based strategies, such as the least-angle strategy (Hochimair, 2005) or egocentric representations (Wang & Spelke, 2000)

Many different explanations have been explored over the years as to how humans break down and execute the process of wayfinding. Weiner and Mallot (2003) describe the fine-to-coarse heuristic, where individuals plan a route to the region containing the target, and only once inside that region determine the subsequent specific route. Garling and Garling (1988) reported empirical evidence of the use of this heuristic by pedestrians in shopping malls.

Holscher et al. (2011) showed how different planning and navigation conditions lead to different wayfinding strategies in an urban environment (Freiburg downtown). Through analysis of verbal data, they found that actual route navigation (situated planning) is predominantly direction-based and characterized by incremental perception-based optimization processes. This is in contrast to in-advance route planning and descriptions (prospective planning), which draw on memory resources to a higher degree and accordingly rely more on salient graph-based structures. In fact, Holscher et al. (2011) found that participants seldom chose the same route that they planned in advance when they actually navigated in the city. They interpreted this finding as evidence supporting that situated route planning is an incremental process that involves local adjustments on the basis of perceptual (visual) information. It is not clear, however, how representations and processes change as local adjustments are made.

Indoor Wayfinding

Wayfinding research specifically in indoor environments has not been explored as thoroughly. Tenbrink et al., for example, pointed out that there were different implications for outdoor versus indoor wayfinding. Much outdoor wayfinding research has proved the crucial impact of landmarks on human understanding of spatial environments: Humans use landmarks to orient and locate their own position, to retrace a route, and to find the correct direction towards a destination. However, the extent to which such findings can be transferred to indoor scenarios remains unclear, except for findings highlighting the particular role of central points (well-known parts of a building) for orientation as well as wayfinding strategies (Garling et al., 1983).

In their study of indoor wayfinding, Tenbrink et al. used verbal think-aloud data from novices and experts, who were asked to find and describe routes in a complex building. By analyzing the spatial descriptions of participants, they were able to relate subjects' level of knowledge to route efficiency and to occurrences of particular linguistic elements. They identified a diversity of wayfinding and description strategies, ranging from generic methods that do not rely on specific spatial elements, to strategies that rely on specific features of the environment (e.g., *the* staircase) or salient central landmarks (e.g., the main entrance), and to strategies that rely on first-person turn-by-turn directional descriptions (e.g., to the right, then left, straight on, etc).

Holscher et al. (2006) studied how experts and novices navigated in multi-level buildings. Similar to Tenbrink et al., think-aloud protocols and performance measures were collected and analyzed. The analysis identified three specific strategies for navigation. The *central point strategy* used well-known parts of the building; the *direction strategy* used routes that first head towards the horizontal position of the target destination; and the *floor strategy* used routes that first head towards the vertical position of the target destination. Participants in their study, however, did not have access to a map. It is therefore unclear how participants would combine the use of a map with perceptual cues while navigating in a multi-level building.

In a series of pilot testing, we found that, even with a schematic map of a complex multi-level building, subjects who had never been to the building before would still have a lot of trouble finding their ways around. One main challenge for indoor navigation with a map is to adopt an effective strategy that allows the person to establish a good mapping between the allocentric spatial representations of the multiple floor maps and the actual environment that they perceive, such that directional judgment can be made to guide navigation. Following the methodology of previous research on wayfinding strategies, we conducted an observational study to focus on how novice participants adopt different strategies to transform the allocentric representations in schematic maps to egocentric representations of the environment that are useful for navigation.

Method

The Beckman Institute at the University of Illinois was chosen as the testing ground for the experiment for a number of reasons: It is one of the largest buildings on the University of Illinois campus, it does not have a straightforward layout, and anecdotal evidence shows that new visitors to the building often get lost. It was also chosen because, the artificial systems (e.g., numbering) designed to help people to navigate inside the building were somehow counterintuitive, making it an interested test bed for how people utilize various cues to navigate in such environment.

To assist subjects during the experiment, digital maps were created for the iPad tablet device, which subjects could carry with them and use during the experiment. Figure 1 shows the maps that they saw during the experiment.

Subjects

24 subjects aged between 20 and 28 (mean=24, female=10) participated in the study. Subjects were recruited from flyers posted in the University of Illinois campus. None of the subjects had been to the Beckman Institute before.

Spatial Ability Test

Following Holscher et al. (2006; 2011) and many others, we used the perspective taking/spatial orientation test (PTSOT) test (Kozhevnikov et al., 2002; Hegarty & Waller, 2004), which was available online. We used the standard measurements to use as a spatial ability score for each subject.

Procedure

When subjects arrived at the building, the experimenter was waiting for them at the main entrance. After finishing the informed consent form, the subject was given a pretest to assess their spatial abilities and given an overview of what would be asked of them during the experiment. They were then given the device with the interactive map and instructed on its use.

With the device in hand, subjects were instructed to perform a series of wayfinding tasks within the building using the mobile schematic maps. Before each task the researcher would take the subject to a start location in the building, then upon arrival would tell the subject their next location to find. The researcher would then follow behind the subject taking notes on the subject's behavior. Subjects were instructed to "think aloud," providing useful information on their strategies and difficulties, which would also be recorded. Only when subjects stopped talking, or when the subjects attempted to go to locations that were not allowed (e.g., into a bio lab), subjects were prompted by the experimenter to either talk more, explain what they were doing, or to choose a different route. All verbal protocols were recorded, and any other non-verbal responses, such as body/head turning, were noted by the experimenter.

The device itself was programmed to collect timestamps on any interaction the user had with the map. The subject was instructed to press a "start" button when each task was given to them, and a "done" button when the end location was reached – time to complete each task was gathered this way. The actual paths taken by the subjects were recorded by the experimenter.

At the end of each task, subjects were debriefed and asked to comment on how they used the maps and what difficulties they had finding the target locations. When all tasks were completed, the subjects were asked to comment on their strategy during the tasks and asked to clear up any final questions the experimenter had about their experience.

Map Design

The map program used by subjects was custom made by the researcher for the iPad tablet device. The choice to use of a tablet computer was made because of its portability, the ability to make custom software, and because they are relatively intuitive to operate – A user just has to touch the screen to activate buttons. The maps were based on the floor plan of the Beckman Institute and built in Microsoft Visio, exported as JPEG files and loaded as part of the program on the device. The decision to show each floor separately was made because showing the entire map as one image would have made it much more difficult for users to read words and symbols on the map.

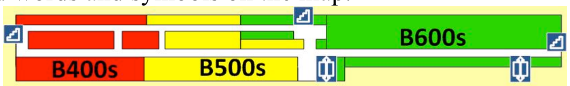
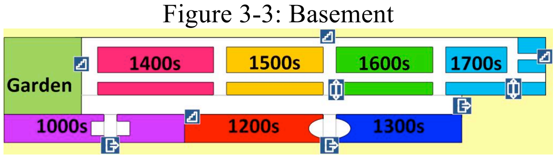
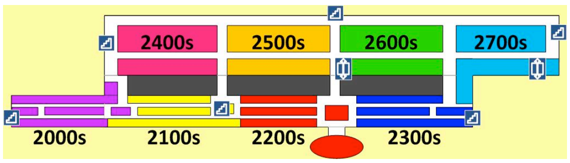


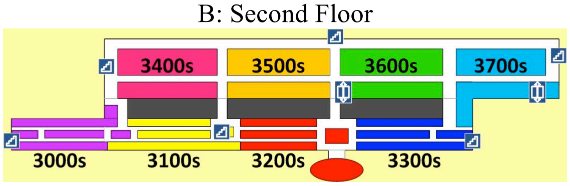
Figure 3-3: Basement



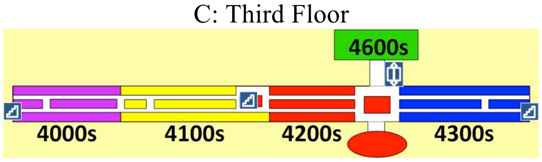
A: First Floor



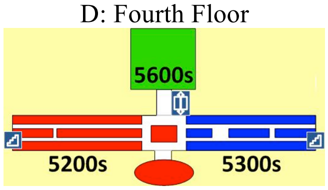
B: Second Floor



C: Third Floor



D: Fourth Floor



E: Fifth Floor

Figure 1. The maps used in the experiment. Participants can switch to any of the floors (A to E) with a touch of a button on the screen of an iPad. The maps showed the location of the elevators, stairs, exit doors, as well as office blocks in different colors and their numbers.

Figure 1 shows the map of each floor. The maps showed the locations of the main building objects, such as elevators, staircases, exit doors, and office blocks. The numbering system of each block was also shown. Note that the numbering of office blocks was in general consistent across floors, but because of the locations of labs, conference rooms, and offices with different configurations on each floor, there were some inconsistencies. For example, 1100s was missing on the first floor. The basement used a different number system. The fourth and fifth floor had a different layout than the rest of the floor. Because of the same reason, the staircases did not all go to all floors. For examples, the one of the far left hand side of the maps only went from the second to the fifth floor, and the one at the middle the map went only from the basement to the third floor. Similarly, while the main elevator went to all floors, the one on the right hand side of the map only went from the basement to the third floor. These specific features made situated route planning challenging, especially for novices.

Tasks

The subjects in this experiment had 10 tasks to complete. The order of these tasks were fixed for all subjects, such that the strategies used by different subjects can be directly compared. These tasks were chosen based on a series of pilot studies. The sequence of tasks would require subjects to use a mix of different strategies and utilize a wide range of environmental cues to finish. The first seven of these tasks required subjects to look for a location and find the shortest route to reach the location. The last three tasks had additional constraints that required participants to come up with a route that satisfy the constraints (e.g., do not use the elevator). These tasks were presented one at a time on the iPad, which would be visible during the task. The experimenter would ask the subject whether they understood what they needed to do, and provide simple explanation to clarify the task if necessary (without giving any hints on how to get to the location). Subjects could not see the next task until the current task was finished (i.e., when they clicked “done” on the iPad and the experimenter agreed that the task was done, the next task would be presented). Subjects were instructed to find the shortest path to reach the target location.

Results

All verbal protocols were transcribed, and all other information recorded from the subjects during the tasks was combined with the verbal transcription. Completion times were extracted for each task. We did not find any significant effect of tasks on strategy use nor completion times, suggesting that the behavior did not differ significantly across tasks. We therefore collapsed all tasks in the analysis.

Route Efficiency

For each task, we computed the best route and compared the route walked by each participant to the best route. Following Holscher (2011) and Wiener et al. (2009), route efficiency was calculated as RE=(D-D’)/D’, where D was the route taken and D’ was the best route. For example, when RE equals 0.5, the chosen route is 50% longer than the best route. A smaller value of RE indicates better efficiency.

The mean route efficiency (RE) across participants was 0.68 (min=0, max=2.46), with a standard deviation of 0.23. We found that RE correlated with the PTSOT measure significantly ($r=-0.68$, $p<0.05$), suggesting that those with higher spatial ability had a better RE (smaller value). We will interpret this result further in the context of how participants performed the tasks. Before that, we will need to describe how we analyzed the verbal protocols to study how participants differed in how they performed the tasks.

Verbal protocol analysis

The verbal protocols were transcribed for each task for each subject. The transcribed protocols were first annotated based on a subset of spatial linguistic categories directly from Tenbrink et al. (2011) (details below). The annotated protocols were then further coded to investigate how much the subjects referred to objects or locations on the map, the environment, or in their mental representation. The coded protocols were further analyzed to identify spatial strategies used in the tasks. For all annotation and coding, two independent coders first performed about 5% of the protocols and reached consensus on the general schemes, and independent coded the rest of the protocols. The inter-rater agreement reached over 0.8 in both cases.

We used the major spatial linguistic categories from Tenbrink et al., which included *spatial elements*, such as *landmarks* (staircases, hallways, or elevators), *start and end points* (e.g., from *here* to *there*); and *directions* (e.g., to the left). We also included the category of *orientation indicators*, such as references to *orientation signs* (e.g., exit signs, office numbers on wall, etc) and *processes of orientation* (e.g., inferring the relative locations of two points). All verbal protocols were annotated by highlighting words or phrases that belonged to these categories in each task. These spatial linguistic categories were used to represent instances of spatial information processing, which were then further coded to study the nature of these processes.

After the annotation, the protocols were further coded into whether the spatial information processes were based on different information *sources*. In particular, we were interested in the representations and processes of spatial information. In this task, there are multiple sources of information that could impact representations and processes. From the schematic maps, objects and locations are primarily represented in an allocentric system, where as perceptual cues of objects and locations in the environment are primarily represented in an egocentric system (Klatzky, 1998). A third possibility is when the allocentric representation in a schematic map is transformed into a mental (imaginal) representation (Klatzky, 1998), from which egocentric references to locations can be made. The mental representation can also help to combine information from the schematic maps with perceptual cues to inform navigation, possibly from an egocentric perspective. Observing when participants chose to process spatial information from the maps, the environment, or the mental representations can therefore help to understand how representations and processes are related to strategies and performance.

The annotated protocols were further coded and categorized into whether participants processed spatial information from (1) the schematic maps (external representation), (2) the environment (perceptual cues), or (3) mental representations (e.g., memory or mental representation of spatial information). 98% of the annotated protocols could be categorized into these three categories. When processing was based on information from the schematic maps, participants would use some form of deictic references (e.g., looking and/or pointing at the map) to objects or labels on the maps, and infer the relative locations of these objects or labels based on their representations on the maps (without referencing their self positions). For example, a participant would say “This is where I need to go” (pointing to the map), “and I need to take the elevator here, so I will need to go through here” (pointing to the map). When processing information from the environment, the participant would refer to perceptual cues such as an information sign on the wall, the hallway, or the elevator, and would say, for example “I should turn left to follow this sign to the room”. When processing was based on mental representations, the participant would adopt some forms of imaginal representations, referring to a location without referencing information on the map or visible cues in the environment. Rather, the references would be based on memories, an imagined direction relative to the current location of the participant, or relative locations with respect to an imagined (or memories of) locations at which the participant were standing. For example, the participant would say “The room should be right above me” or “The cafeteria is right below me, so the room should be somewhere in that area” (pointing to the lower left direction).

Each of the annotated protocols were inspected and coded into one or more of the three information sources. For each participant, we counted how many times each of these information sources were used in each task. We then compared how these uses changed across tasks, and how they correlated with their performance.

Spatial ability, processes, and performance

To understand how processes impact the relations between spatial ability and performance, we performed a regression analysis of the effects of spatial abilities and the number of times processes were based on information from the maps, the environment, and the mental model. We hypothesized that the effect of spatial ability on performance (route efficiency) could be mediated by how participants processed spatial information. We therefore performed a mediation analysis to understand the extent to which the use of maps, environmental cues, and mental representations mediated the effect of spatial ability on performance.

Figure 2 shows the standardized regression weights from the analysis. We first regressed spatial ability on route efficiency, and found a significant β=-0.68. The measures of use of maps, environmental cues, and mental representations were entered in one at a time to test how they mediated the effect. Spatial ability had an effect on the use of maps and mental representations (β=0.43 and β=0.51, respectively) but not on the use of environmental cues. The use of maps and mental representations had an effect on route efficiency (β=-0.16 and β=-0.35, respectively), but the use of environmental cues did not predict route efficiency.

When the use of maps was controlled for, the direct effect of spatial ability on route efficiency was reduced to β=0.61, but the effect was still significant at p<0.05. When the use of environmental cues was controlled for, there was little change in the direct effect of spatial ability on route efficiency. The reduction of effect for both cases (use of maps and environmental cues) was not significant according to the Sobel Test (Sobel, 1982). However, when the use of mental representations was controlled for, the direct effect of spatial ability on route efficiency became non-significant (β=-0.51, p=0.09). The reduction of effect was significant (Δ=0.17, p<0.05) according to the Sobel Test. The result suggested that the use of mental representation was a significant mediator of the effect of spatial ability on route performance.

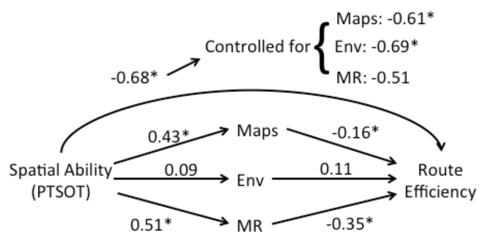


Figure 2. Regression analysis that tested how the use of maps, environmental cues (Env), and mental representations (MR) mediated the effect of spatial ability (measured by PTSOT) on route efficiency. The numbers represented standardized regression weights. Numbers with an asterisk (*) were significant at p<0.05.

To better visualize how the processing of information from different sources impact performance, we performed a median split based on route efficiency, and created two groups of participants – the low and high route efficiency groups. The average number of each type of processing was plotted against the 10 tasks (see Figure 3).

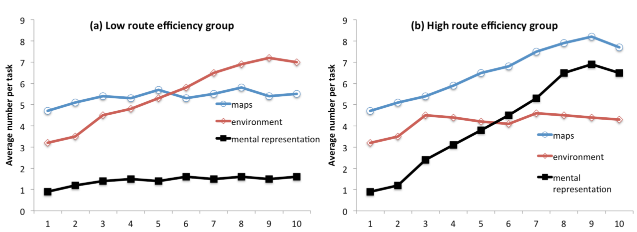


Figure 3. The average number of spatial information processing using the maps, the environment, and the mental representation in the low and high route efficiency groups.

As shown in Figure 3, the low and high efficiency groups showed very different patterns in how they processed spatial information. Participants in the low efficiency group relied mostly on the maps and the environment to do route planning, and the use of mental representations was much lower throughout the tasks. There was also a trend that the use of environmental cues increased across tasks. In contrast, participants in the high efficiency group relied more on the use of the maps and mental representations, which increased across tasks. The use of environmental cues, however, did not increase as in the low efficiency group.

The pattern of results suggested that participants in the high efficiency group relied more on the use of mental representations, while participants in the low efficiency group relied more on the use of environmental cues in situated route planning. Given that the regression analysis showed that the use of mental representations mediated the effect of spatial ability on performance, the differences shown in Figure 3 showed that participants with better spatial ability were able to develop better mental representation of the building, which led to better performance.

We inspected the protocols of the participants in the low and high efficiency groups to investigate whether there were qualitative differences in how they performed the tasks. In general, we found that participants in both groups relied on the maps to infer the locations of important landmarks to derive a partial route plan. What differed most was how they executed the plan as they navigated towards the target location. Participants in the low efficiency group tended to combine visual cues and general navigation strategies (strategies independent of the building layout) to navigate. For example, they would start walking in one direction and search for an information sign that would help them to get closer to the target location. Only when necessary (e.g., when they were lost), they would try to look at the maps and look for labels or landmarks that will help them to identify where they were.

In contrast, participants in the high efficiency group tended to construct a mental representation of the route as they studied the maps and the surroundings, and executed their plan according to the mental representations. For example, they would transform the allocentric representations of relative locations of landmarks on the maps to egocentric representations of relative directions in the actual environment. By doing so, they could orient themselves towards these locations with respect to their current locations and infer the general directions to go based on the transformed egocentric representations. Our results showed that the success of this transformation process predicted their performance, and the effect of spatial ability (using the measure of perspective taking and spatial orientation) on performance was found to be mediated by the use of mental representations.

Discussion

The current study aimed to explore how novice participants used mobile maps to perform situated route planning in a complex, multi-level building. We found that the use of mental representations of the building was important for route planning and navigation. The construction of mental representations seemed important for participants to transform the allocentric, schematic representations of the environment in the maps to mental representations, such that they could more effectively make directional judgment to guide navigation. We also found that participants with higher spatial ability would more likely perform this transformation, and as a result, performed better.

Although this study was not focused on categorizing the spectrum of wayfinding strategies as in previous studies (e.g., Holscher, et al., 2011; Tenbrink et al., 2011), the current findings were in general consistent with them. In particular, we did find that wayfinding strategies ranged from generic strategies such as reading of information signs, to the use of landmarks and features that were specific to the building, such as the use of common building structures (e.g., elevator, staircase) or central points (e.g., main entrance). The main contribution of the current study, however, was on the process of situated route planning when mobile maps were available. In particular, we found that while some participants relied on deictic strategies to process spatial information in schematic maps and the environment, some chose to transform the spatial information into mental representations to facilitate situated route planning.

Our results suggested that mental representations were more useful for indoor wayfinding. However, given that we only conducted the study in one building, it was not clear to what extent the results could be generalized to other buildings. In fact, it was possible that some of the awkward visual cues and information signs in Beckman Institute could make the deictic strategies less effective, and egocentric mental representations could be more reliable (even thought they could be more cognitively demanding to construct). Future research on different buildings can help shed light on the generalizability of results. Nevertheless, the current findings did point to an interesting research direction on the effects of spatial information representations and processes on indoor wayfinding with maps.

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