# Getting There and Beyond: Incidental Learning of Spatial Knowledge with Turn-by-Turn Directions and Location Updates in Navigation Interfaces

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## ABSTRACT

Spatial user interfaces that help people navigate often focus on turn-by-turn instructions, ignoring how they may help incidental learning of spatial knowledge. Drawing on theories and findings from the area of spatial cognition, the current paper aims to understand how turn-by-turn instructions and relative location updates can help incidental learning of spatial (route and survey) knowledge. A user study was conducted as people used map-based and video-based spatial interfaces to navigate to different locations in an indoor environment using turn-by-turn directions and relative location updates. Consistent with existing literature, we found that providing only turn-by-turn directions was in general not effective for helping people to acquire spatial knowledge as relative location updates, but map-based interfaces were in general better for incidental learning of survey knowledge while video-based interfaces were better for route knowledge. Our result suggested that relative location updates encourage active processing of spatial information, which allows better incidental learning of spatial knowledge. We discussed the implications of our results to designs trade-offs in navigation interfaces that facilitate learning of spatial knowledge.

## CCS CONCEPTS

• **Human-centered computing** → **User studies**;

## KEYWORDS

Spatial knowledge; incidental learning; navigation application; interface design; relative location update; turn-by-turn directions; egocentric; allocentric

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## 1 INTRODUCTION

Spatial knowledge, in the broad sense, refers to the kind of knowledge about the environment that is directly or indirectly related to the spatial structures of the environment. Spatial knowledge is often acquired incidentally as one navigates in or interacts with an environment. For example, people learn how to navigate to supermarkets, post offices, or restaurants, as they engage in everyday tasks, and may learn about the locations of police stations or hospitals for emergencies. In fact, spatial knowledge is often found to be naturally acquired and integrated into various aspects of our lives to support activities that are relevant to us personally and socially.

In practice, navigation interfaces primarily focus on how to guide people to go from one location to another through turn-by-turn instructions. When provided with accurate spatial information (e.g., from maps and GPS locations), these turn-by-turn instructions have shown to be successful in helping people get to their destinations. However, they are not designed to provide the same cognitive experiences that people have when they naturally learn to integrate spatial information into their daily activities. The lack of cognitive compatibility has several potential drawbacks. First, when the navigation system has imperfect information (e.g., when GPS location information is imprecise or when map information is outdated), the turn-by-turn instructions will be inaccurate and will likely lead users to the wrong locations. If the users do not have adequate spatial knowledge, they may have trouble recovering from these potential errors. Second, because of the potential poor incidental learning of spatial knowledge, the users will likely not be able to effectively communicate to or help others navigate in the same environment. In other words, navigation interfaces that solely provide turn-by-turn instructions not only are less robust, but they also do not empower users with the spatial knowledge that they naturally acquire from an environment. The main goal of this paper is to systematically investigate the design trade-offs of navigation interfaces that not only help people reach their destinations but may also help people naturally acquire spatial knowledge of the environment.

Our review of the literature shows that there is still a lack of systematic research on how to design navigational interfaces that help people learn spatial knowledge incidentally when

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they navigate in an environment. To this end, we designed and conducted a user study that tested how different ways to present spatial information in different frames of references (FOR) can help people learn spatial knowledge. While the design space of different presentations of spatial information is enormously large, our goal is to adopt a theoretically driven approach to understand how different components of spatial knowledge may be more likely incidentally acquired. However, both indoor and outdoor navigations have their unique challenges for learning of spatial knowledge. To limit the scope of our work, we will focus only on indoor navigation in this paper. We hope to do a similar study focusing on outdoor navigation only in future.

One critical challenge of indoor environments often have homogeneous structures and landmarks that make them difficult to learn [38]. Our results showed that different combinations of FOR and navigational cues can significantly impact the incidental learning of survey and route knowledge during regular wayfinding tasks. However, before describing our results in detail, we will discuss relevant backgrounds and theories on spatial knowledge next, which guided our interface design.

## 2 COMPONENTS AND STRUCTURES OF SPATIAL KNOWLEDGE

Spatial knowledge is complex, as it consists of how multiple spatial information is processed, encoded, and utilized in different situations. It allows people to accomplish spatial tasks, such as wayfinding and self-localization. In this section, we review the components and structures of spatial knowledge.

### 2.1 Components of Spatial Knowledge

There are two main components of spatial knowledge: survey knowledge and route knowledge. We will describe each type of knowledge next.

*2.1.1 Route Knowledge.* Route knowledge refers to knowledge about the movements necessary to get from one point to another. This knowledge is often derived from navigational activities and encoded as a sequential record of the space between a starting point, subsequent landmarks, and destinations. Moeser et al. [20] found that people can develop good route knowledge by directly navigating in a complex building.

*2.1.2 Survey Knowledge.* Survey knowledge, also known as a "bird's eye view", refers to knowledge about the topographic properties of an environment, which include the location of objects in the environment relative to a coordinate system, the global shape of a large area, and inter-object Euclidean distances. In a rescue mission, survey knowledge would help rescuers to determine the general direction of the exit to be used for an emergency evacuation, even when environmental cues have changed.

Both survey and route knowledge are important for people to effectively navigate or help others to navigate in an indoor environment. There is a large body of literature on how people acquire these two types of spatial knowledge from navigating in an environment (e.g., [8, 9, 13, 20, 22, 33]. There is, however, still a general lack of understanding how tools can be built to facilitate incidental learning of spatial knowledge during navigation. The goal of the current study is to test the effects of different types of spatial FOR and navigational cues on incidentally learning of spatial knowledge.

### 2.2 Structures of Spatial Knowledge

Spatial knowledge consists of spatial information of the environment. The unique aspect about spatial knowledge is that spatial information needs to be organized by different *frames of references (FOR)*, which shape the *structures* of spatial knowledge.

*2.2.1 Frame of Reference.* The location of an object cannot be referenced independently. For example, we cannot describe the location of Berlin without referencing another location (e.g., London or Munich) or a coordinate system (e.g., a map of the world or Europe). The Frame of Reference (FOR) is a means of representing the locations of entities in space [13]. It is widely used to distinguish between two spatial representations: egocentric and allocentric representations.

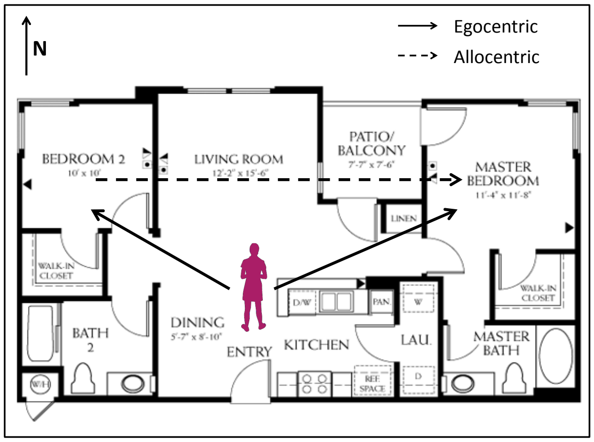


**Figure 1: The difference between egocentric and allocentric representations is explained using the map in this figure.**

*Egocentric Representation.* In egocentric representation, people encode or represent the positions of objects in relation to themselves [40]. In Figure 1, the solid lines on the map show an egocentric representation in which the locations of Bedroom#2 and the Master Bedroom are defined relative to the position of the observer. Egocentric perspective is particularly useful for acquiring route knowledge because both environmental cues and possible actions can be encoded with the *same* structure – the egocentric representation.

*Allocentric Representation.* In allocentric representation, the locations of objects in space are coded in object-centered coordinates that may or may not be independent of the observer's current position [5]. In Figure 1, the dotted line on the map shows an allocentric representation in which the location of the Master Bedroom is defined relative to the position of Bedroom#2. Given that allocentric representations use a single FOR (e.g., map) to specify the relative locations of multiple objects and the observer in an environment, they are particularly useful for route planning.

# 3 RELATED WORK

## 3.1 Spatial Learning through Navigation and Wayfinding

One may think that spatial knowledge will be acquired effortlessly with repeated visits. However, existing literature in spatial cognition suggests that this is an incorrect assumption [7, 19]. In fact, studies found that people often get lost in hospitals, libraries, or shopping malls even after multiple visits [1, 24, 24, 38]. These findings suggest that technologies that help people to acquire spatial knowledge not only are useful but in many cases necessary and critical.

While an obvious solution to help people to acquire spatial knowledge is to give them a map of an environment, it is often not sufficient. However, Streeter et. al. [31] found that people who were asked to navigate unfamiliar roads performed better with route directions than with a map. Thorndyke et al. [33] showed that although maps helped people to learn the relative distance between objects, having actually navigated in the environment helped them to acquire a better sense of orientation within it. Li et al. also found that reading maps for navigation tasks are not a straightforward task [18]. What we can take from this is that people also need first-person experiences in addition to the spatial layout of the environment to acquire spatial knowledge. For example, people need to acquire knowledge about landmarks [34] and navigational cues that they will see, as they often integrate them as parts of the spatial knowledge of the environment and use them to navigate different destinations (with or without a map).

## 3.2 Navigation in Virtual and Augmented Reality

Because maps only provide an abstract spatial representation of the environment, tools such as virtual and augmented reality based navigation applications along with dynamic navigational cues have the potential to allow people to more effectively learn spatial knowledge. Navigating in a virtual world enables people to gain the experience of navigating to a location without physically being there. Many previous studies have explored the effectiveness of a virtual environment (VE) for spatial learning. For example, Richardson et al. [27] studied how people acquire spatial knowledge when navigating in a VE with augmented navigational cues and when navigating in a real environment with a map. They found that people were more susceptible to disorientation after rotation when they were learning from augmented VE compared to navigating directly in an environment. This suggested that the map combined with the experience of real-world navigation was more useful for the acquisition of spatial knowledge than augmented VE. Similar to Witmer [39], Philbin [25] and Richardson [27] found that VE training is weaker than map-study. However, Darken et al. showed [3] that VEs can help people to learn spatial knowledge that they can later use to navigate in the real world. This indicates that a better representation of navigation applications in VR could overcome the existing challenges.

Although augmented reality(AR) and virtual reality(VR) are closely related, their differences are sufficiently significant that spatial learning through AR merits separate study. Shelton et al. [30] established a baseline for this field of research in finding that AR is appropriate for representing spatial information. Previous literature [6, 12, 14, 32, 37] has found that AR can reduce cognitive load and mental effort more than interfaces such as written instruction or computer-assisted instruction on an LCD screen. The wide use of mobile devices, as well as the advancement of head-mounted displays such as Google Glass and Microsoft HoloLens, have made spatial learning through AR a feasible and promising subject of study.

## 3.3 Navigation Applications: Frame of References

Navigation applications rely on the GPS, built-in sensors of mobile devices, and wireless infrastructures for developing back-end self-positioning algorithms [4, 28]. To present this information in a human-perceivable way, navigation applications primarily use maps or schematic floor plans as an allocentric frame of reference since this is similar to paper maps. Munzer et al. [23] used a map of a university campus to study the trade-off between wayfinding support and configural learning support. Ishikawa et al. [10] used a similar map based frame of reference in their navigation system to measure the performance and comfort level of the users in navigation tasks. Schwering et al. [29] also used a map-based frame of reference to study the effect of orientation information on acquiring spatial knowledge in outdoor environments.

Google Maps uses a map-based frame of reference to provide directions to destinations by default. However, along with the map, Google Maps also features satellite images to provide an egocentric route information of outdoor locations. Moller et al. [21] used an extension of this feature where they used live camera images to design a navigation assistant. Rehman et al. [26] also used live camera images presented through a mobile device and a Google glass to compare the effectiveness of these devices in proving navigational guidance. Researchers [6, 12, 14, 32, 37] have found that live camera images can reduce cognitive load, mental effort, and divided attention more than interfaces such as written instruction or computer-assisted instruction on an LCD screen.

Although map based and live camera image-based frame of references were used widely to study the effectiveness of navigation systems in different context, there is still a lack of understanding how these FORs impact the incidental acquisition of spatial knowledge. Moreover, to the best of our knowledge, no work has been done to investigate how dynamic navigational cues, such as relative location updates, may help incidental learning of spatial knowledge. We believe that our study will contribute to this corpus of prior work by comparing the significance of these frame of references alongside navigational cues in acquiring spatial knowledge.

## 4 INTERFACE DESIGN

We designed our external representation with two types of elements: frame of references (either an egocentric or an allocentric spatial representation) and navigational cues. To better understand how the interface design of navigation applications can assist people in the acquisition of incidental spatial knowledge, we developed the following research questions:

RQ1: *What are the effects of the frame of references in navigation applications on incidental learning of spatial knowledge?*

RQ2: *What are the effects of the integration of location and orientation cues with different FOR on incidental learning of spatial knowledge?*

### 4.1 Frame of References: The Map and Video Interfaces

We decided to use a map (allocentric) and a live video camera (egocentric) based interface designs for the current study. Our goal is to understand how turn-by-turn instructions in each representation can help incidental learning of different components of spatial knowledge, and to what extent other navigational cues that require more active processing of spatial information can improve incidental learning of these components in each representation.

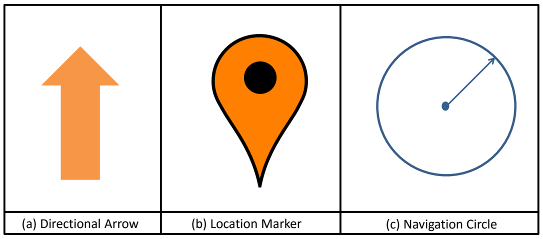


**Figure 2: Shown are (a) a directional arrow, (b) a location marker, and (c) a navigation circle.**

### 4.2 Navigational Cues: Directional Arrows and Relative Location Updates

In navigation applications, interactive navigational cues are placed on top of a frame of reference to guide users during navigation. In this study, we designed and tested two main types of navigational cues.

*4.2.1 Turn-by-turn Directional Arrows.* We found that directional arrows (Fig 2a) are the most common cues in existing navigation applications for helping people to make decisions turn-by-turn. We studied the effect of directional arrows for both map and video interfaces. We began with the assumption that directional arrows would help users to reach their destination but would not be effective for incidental learning of spatial knowledge as users are less likely to actively process spatial information in the environment during navigation.

*4.2.2 Relative Location Updates.* In general, during navigation, a person needs to know the orientation of the destination relative to their current location to make navigational decisions. With turn-by-turn instructions, however, the cognitive processes involved in these decisions are offloaded to the navigation system and therefore the person is less likely to actively process spatial information in the environment. On the other hand, if only the locations of a person's current position relative to the destination are shown on a navigation interface, the person will more likely integrate spatial information from the environment with that on the interface to make their own navigational decisions. We hypothesize that showing relative location updates will likely encourage incidental learning of spatial knowledge.

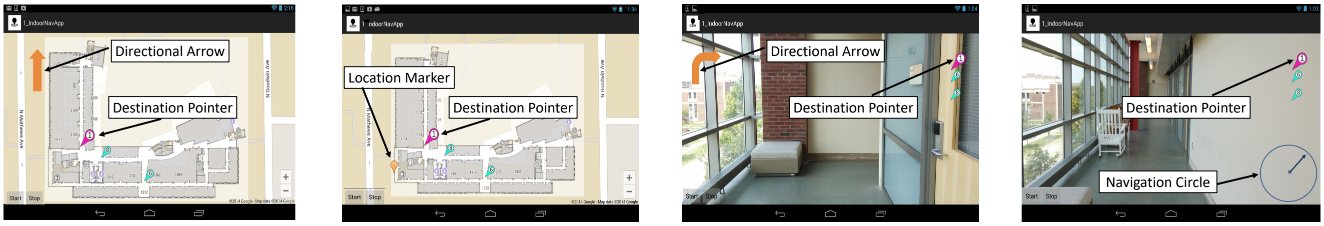
To test the effects of relative location updates, we surveyed the literature and existing applications to choose the typical representation of relative location updates. For the map interface, we took inspiration from static you-are-here (YAH) maps placed at important junction points of large buildings [16, 17]. The self-localization technique has made it feasible to implement a dynamic YAH feature through a location marker pin for the map-based interfaces (as shown in Fig 2b).

In contrast to the map interface, users of the video interface cannot see anything outside of their line of sight. Therefore, inspired by the radar visualization used by air traffic controllers, we have designed a navigation circle (Fig 2c) for the video interface. The navigation circle is designed as a circular dial where the center of the circle denotes the current position of the user and the hand points to the destination relative to the user's current location in real time. We believed that this navigation circle would help users to overcome their limited view by providing an overall egocentric perspective.

Although both the map interface's location marker and the video interface's navigation circle provide relative location updates, they differ fundamentally in their perspective. The location marker provides a relative location update in an allocentric representation, whereas, the navigation circle provides directional guidance from an egocentric perspective. We hypothesized that both location marker and navigation circle would better assist users to acquire incidental spatial knowledge through active processing of the navigation process than turn-by-turn instructions.

### 4.3 Detailed Interface Design

We designed four interfaces for this study using the spatial representations of frame of references and navigational cues explained in sections 4.1 and 4.2. The first two interfaces used map-based frames of reference whereas the next two interfaces used video-based frames of reference. Next, we discuss the design details of each interface.



**(a) Map Interface with Directional Arrow** **(b) Map Interface with Location Marker** **(c) Video Interface with Directional Arrow** **(d) Video Interface with Navigation Circle**

**Figure 3: Map interface with (a) the directional arrow and (b) the location marker (showing the current location of the user). The Video interface with (c) the directional arrow and (d) the navigation circle. The directional arrow was updated when participants had to take a turn; the marker and the navigation circle were updated after every step taken by the participants. The size and the color of the destination pointers were changed to notify the user that they have already reached to that destination.**

*4.3.1 Map Interfaces.* In map interface, we displayed the allocentric schematic floor plan of the third floor of an academic building. To mark any specific location on the map, we superimposed colored pins on the interface. We created two variations of this map interface using navigational cues. The details of the two map interfaces are discussed below.

*Map Interface with Directional Arrow.* For the first variation of the map interface, we superimposed a directional arrow on top of the schematic map to guide the user. Three types of arrows were used for this purpose: 1) a straight-ahead arrow pointing to the top of the tablet, 2) a left arrow, and 3) a right arrow. Most of the time during the experiments, participants saw the straight-ahead arrow, which indicated that they needed to walk straight ahead. Whenever they were required to make a turn, a turning (left or right) arrow appeared few steps before the required turn. Once a participant took the turn, the arrow would change to the straight-ahead version until the next turn. A screenshot of the interface is shown in Figure 3a. We anticipated that this interface might not directly support route planning.

*Map Interface with Location Marker.* To represent a relative location update, we chose a default Android location marker superimposed on top of the schematic map in real time. This marker showed the current location of the participant on the schematic map in real time after every step (Fig 3b). Participants had to keep track of the location marker to decide when to take a turn to reach their desired destination. Using this interface, participants could perform complete route planning, but this interface might not assist them in aligning the egocentric and allocentric representations.

*4.3.2 Video Interfaces.* In our video interfaces, participants always viewed a live camera feed on the tablet. Colored pins were superimposed on the right side of the interface. These pins indicated whether or not the user had already reached some specific destinations during the navigation. The details of the video interfaces are discussed next.

*Video Interface with Directional Arrow.* This interface displayed a directional arrow similar to the corresponding map interface. The only difference was that the interface displayed a video feed instead of a schematic map (Fig. 3c). We expected that this interface design might not help users to acquire route knowledge. We expect that this interface design would not be suitable for acquiring survey or route knowledge.

*Video Interface with Navigation Circle.* In this video interface, we replaced the directional arrow with a navigation circle (Fig 3d) that indicated the direction of the immediate destination relative to the participant's current location in real time from an egocentric perspective. Using this interface, participants were unable to perform complete route planning as they did not know their current locations. However, this interface provided participants with an egocentric representation. We, therefore, expected that this interface design might help users to acquire route knowledge.

## 5 METHOD

To understand the spatial learning process, we conducted a between-subject study using a custom-designed indoor navigation application using a Nexus 7 tablet. The localization algorithm used for all versions of our application is based on the dead-reckoning technique [2, 15]. The main challenge of using the dead-reckoning technique is that as the accelerometer readings are integrated to calculate the user's current position, errors accumulate over time. We adjusted for those errors periodically by detecting participants' turns using gyroscope readings. We also calibrated the stride length of participants individually before starting the experiments. After multiple cycles of pilot testing, we built a robust navigation application with the localization error of 1.5 meters, which is comparable to standard off-the-shelf localization algorithms [35]. Figure 4 shows a participant of our user study using a randomly assigned navigation interface to complete our assisted navigation tasks.

### 5.1 Participants

To recruit participants, we posted flyers in community restaurants and libraries and sent emails to local communities. We recruited 32 participants (18 females) between 18 and 55 years

**Figure 4: A participant completing an assisted navigation task using our navigation interface.**

of age, M = 24.97, SD = 6.49 from a university town through this recruitment process. All participants were familiar with using applications in smartphones and tablets. Participants were recruited only when they reported through an online survey that they had never been to the building used for the experiments. Participants were randomly assigned to one of the four interfaces. For each interface, we assigned exactly eight participants. Participants received $8/hour for their participation.

## 5.2 Procedure

In the beginning, our experimenter explained a randomly assigned navigation interface to each participant. We first asked all participants to complete four assisted navigation tasks using one of our interfaces to reach multiple predefined destinations. After completing all the assisted navigation tasks, each participant completed three unassisted navigation tasks for which no navigation application was provided.

After each assisted navigation task, the participants completed two spatial knowledge tests. We used these tests to measure their incrementally acquired survey knowledge. After completing all four assisted navigation tasks, participants completed a floor plan recall test, which we used to measure their integrated learning of survey knowledge. In the end, participants completed three sets of location recognition tests as well as unassisted navigation tests as part of unassisted navigation tasks. Figure 5 shows the sequence of all the navigation tasks and spatial knowledge tests completed by each participant. Next we describe all of the navigation tasks and spatial tests.

## 5.3 Navigation Tasks

We describe the assisted and unassisted navigation tasks in this section.

### 5.3.1 Assisted Navigation Tasks.

We designed four assisted navigation tasks for each participant. Each task required the participant to follow a predefined path in the building. The tasks were designed to have participants walked through all hallways on one floor of the building. The sequences in which participants completed the tasks were randomized. Our participants were new to the building and therefore they did not have any spatial knowledge of it. We labeled each destination point with a salient physical landmark object that does not normally appear in an academic building such as a cardboard butterfly. Each object was affixed to a five-foot pole put at various locations on the floor of the building.

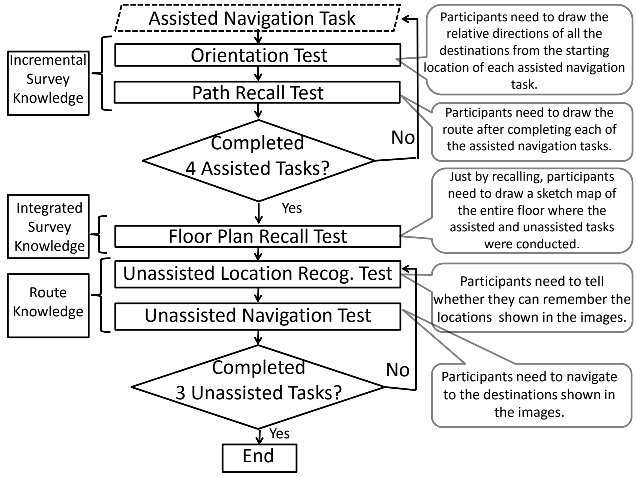


**Figure 5: This flowchart shows the navigation tasks and corresponding spatial knowledge tests.**

### 5.3.2 Unassisted Navigation Tasks.

Each participant also completed three unassisted tasks without the assistance of any navigational interface. For each unassisted task, participants were presented with a picture of a location in the indoor environment that they had encountered during the assisted tasks. They were asked to find the locations shown in the pictures by themselves.

In order to decide the three destinations for the unassisted tasks, we followed the strategy followed by Weisman [38] and chose locations of different levels of difficulty. The first location was easy to remember because of its unique architectural structure. The second location (a common sitting area) was slightly harder as there were multiple similar-looking sitting areas in that floor. The last location was the hallway in front of the service elevator. Since this hallway was one of the darkest hallways on the side of the building, we expected that this place would be the hardest to recognize for our participants.

## 5.4 Spatial Knowledge Tests

During the assisted and unassisted navigation tasks, we asked participants to complete five spatial knowledge tests to measure their acquired spatial knowledge. We classified these tests as measuring certain types of spatial knowledge, aware that some tests might measure more than one type of spatial knowledge. When this seemed to be the case, we classified the test with the most prominent knowledge type.

*5.4.1 Tests to Measure Survey Knowledge.* To measure participant's incremental survey knowledge, we asked each participant to complete two spatial knowledge tests: an orientation test and a path recall test. We classified them as incremental because they measured the survey knowledge acquired only for the part of the environment that participants had just visited for recently completed navigation tasks. After completing all of the predefined assisted navigation tasks, each participant completed an integrated survey knowledge test called the floor plan recall test, based on the participant's acquired survey knowledge for the entire floor.

*Orientation test.* We conducted the orientation test as described by Thorndyke et al [33]. In this test, we asked participants to mark the locations of three landmark objects along with their names that they had seen during the previous task with respect to the starting location and walking direction. To measure the outcome in the orientation test, we calculated the ground truth of all the orientation tests offline from the schematic map and took the difference between the ground truth and the participant's reported angle as the orientation error.

*Path recall test.* The path recall test's design was based on the map-learning procedure followed in [33]. In the path recall test, participants drew the path they traversed during the task they had just finished. We asked them to point out the starting point along with the locations of the three landmarks they encountered along their path. We then compared the corresponding segments of the original path (recorded by the navigation application) and the path reported by participants and calculated the difference in the number of left/right turns and the difference in the number of corridors.

*Floor plan recall test.* In this test, participants were asked to draw the complete floor plan of the building in which the experiments were conducted. They were also told to indicate as many landmark objects as possible in their drawing. One member of our research team and an independent rater rated all the sketches on a 5-point Likert-type scale ( [36]) using two criteria: (a) to what degree the sketch resembled the original map and (b) to what degree potential landmarks were represented in the correct position. A Cohen's kappa test showed the inter-rater agreement as 0.74. So we took the average score for each sketch.

*5.4.2 Tests to Measure Route Knowledge.* The next set of tests explored how the interface designs affected the acquisition of route knowledge. To measure route knowledge, we conducted two tests: 1) a location recognition test and 2) an unassisted navigation test.

*Location recognition test.* In this visual memory recall test, we showed participants pictures of three different locations and asked whether they remembered the locations shown in a picture. Participants were asked to choose one of three answers that best represented their response: (1) remember the place, (2) do not remember the place, or (3) not confirmed but remember the place to some extent.

**Table 1: Avg. time taken to complete the navigation tasks using our navigation interfaces**

| Tasks | Map with Arrow | Map with Location Marker | Video with Arrow | Video with Navigation Circle |
|---|---|---|---|---|
| **Task 1** | 4 min 15 sec | 5 min 30 sec | 4 min 20 sec | 5 min 44 sec |
| **Task 2** | 4 min 48 sec | 4 min 38 sec | 4 min 37 sec | 4 min 22 sec |
| **Task 3** | 4 min 44 sec | 4 min 15 sec | 5 min 10 sec | 4 min 15 sec |
| **Task 4** | 4 min 57 sec | 4 min 49 sec | 4 min 57 sec | 4 min 39 sec |

*Unassisted navigation test.* For this final route knowledge test, we considered how many times participants could reach the desired destination without any assistance. Each participant had to find three different destinations. If the participant could reach the destination successfully, we considered it to be a "success", otherwise, we considered it to be a "failure".

# 6 RESULTS

## 6.1 Time Analysis

To understand how efficiently navigational cues can assist people to complete their navigation tasks, we compared the amount of time taken to finish our navigation tasks by our participants for all four interfaces across four different tasks. Table 1 shows the average time taken by our participants for each tasks using four different interfaces. We ran two-way 4(interfaces) X 4 (tasks) ANOVA and found that there was a significant interaction between interfaces and tasks for the amount of time taken by our participants to finish their navigation tasks (F(9,112) = 11.24, $p < 0.01$). Simple effect analysis showed that there was a significant difference only for the first task (F(3,112) = 8.31, $p < 0.05$) across different interfaces. Participants using the map interface with directional arrow took significantly less time than participants using map interface with location marker ($p < 0.05$). Similarly, participants using video interface with directional arrow took significantly less time than participants using video interface with navigation circle ($p < 0.05$). This indicates that when participants used navigational cues that required active processing (such as location marker and navigation circle), it took participants longer to learn how to use those cues to reach to the destination only for the first task. Our results showed that our participants managed to learn to use these cues quickly and did not take significantly more time to finish their navigation tasks compared to participants who used directional arrows for the rest of the tasks.

## 6.2 Performance in Navigation Tasks

To analyze the results of all the spatial knowledge tests, we first performed a 2 (interfaces) x 2 (navigational cues) MANOVA test with all the dependent variables. The multivariate analysis showed that there is no significant two-way interaction among independent variables. However, we found significant main effects for both interfaces (F(5,24) = 9.89, $p < 0.01$, Wilks l = 0.33, h2 = 0.67) and navigational cues (F(5,24) = 7.07, $p < 0.01$, Wilks l = 0.40, $\eta^2 = 0.60$). To further test how the independent variables impacted each of

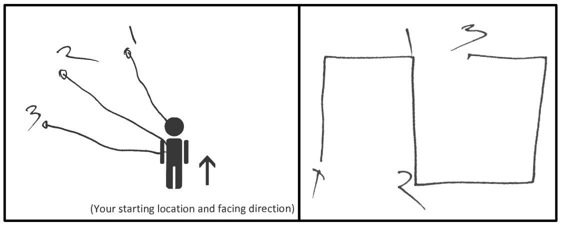
**Table 2: Mean and standard deviation of the measurements in navigation tasks**

| Tasks | Map with Arrow M (SD) | Map with Location Marker M (SD) | Video with Arrow M (SD) | Video with Navigation Circle M (SD) |
|---|---|---|---|---|
| Orientation Test | 39.16<br>(14.14) | 32.46<br>(14.98) | 47.13<br>(18.65) | 29.54<br>(7.61) |
| Path Recall Test | 6.87<br>(1.64) | 3.87<br>(2.79) | 7.50<br>(3.29) | 3.25<br>(2.86) |
| Floor Plan Recall Test | 3.43<br>(1.08) | 3.81<br>(0.59) | 2.06<br>(0.62) | 2.31<br>(0.99) |
| Location Recognition Test | 0.50<br>(0.75) | 0.75<br>(0.88) | 1.50<br>(0.75) | 1.87<br>(0.35) |
| Unassisted Navigation Test | 1.50<br>(0.53) | 1.87<br>(0.64) | 2.00<br>(0.92) | 2.75<br>(0.46) |

the spatial tests, we conducted multiple 2x2 ANOVAs for each spatial knowledge test followed by post-hoc analysis.

We will first explain the results for survey knowledge tests. This analysis will help us understand how the interface design can impact the acquisition of both the incremental and the integral survey knowledge in a new environment. Then we will discuss the results of the route knowledge tests. Table 2 shows the mean and standard deviation of the measurements of the participants in all the navigation tasks.

*6.2.1 Incremental Survey Knowledge Analysis.* For measuring incrementally acquired survey knowledge, we conducted two tests: 1) the orientation test and 2) the path recall test. The results of these tests are explained here.



(a) (b)

**Figure 6: Shown are (a) a orientation test, with sample drawing completed by one participant, and (b) a path recall test, completed by the same participant during one experiment.**

*Orientation Test.* In Figure 6(a), we show a sample drawing completed by one participant in the orientation test. We performed a 2 (interfaces: map and video) X 2 (navigational cues: arrow and relative location updates) ANOVA for the orientation test. We did not find any significant interaction effect. However, we found significant main effect for navigational cues (F(1,28) = 5.68 $p < 0.02$). The main effect for the interfaces was not significant.

We conducted further post-hoc analysis and found that participants using video interface with navigation circle performed significantly better in orientation test than participants using video interface with arrow (F(1, 28) = 5.96, p = 0.02 (as shown in Figure 7a and in Table 2). No other comparison was statistically significant in the orientation test. Since we used errors as the dependent measure here, the lower the values the better were their performances.

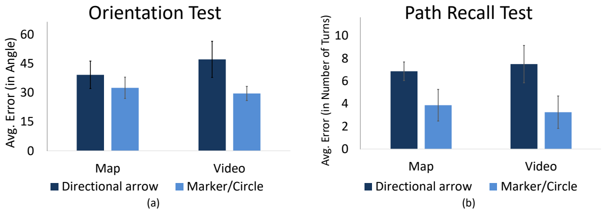


**Figure 7: Bar plot shows the mean error in orientation test (a) and path recall test (b) for all the interfaces. Since both orientation and path recall test measure errors, the lower values are better than the higher values.**

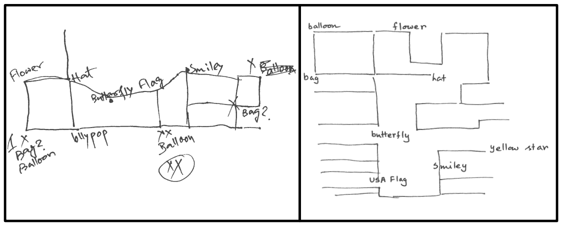
*Path recall test.* Figure 6(b) shows a sample path recall drawing completed by a participant during the study. We conducted a similar 2X2 ANOVA analysis for the path recall test. The path recall test also yielded significant differences among the effects of navigational cues (F(1,28) = 14.20 $p < 0.01$). However, no significant difference was found between the map and the video interfaces. The interaction was also not statistically significant.

Further post-hoc analysis showed that participants using the video interface with a navigation circle performed significantly better than those using the video interface with directional arrow (F(1,28) = 9.76, $p < 0.01$)(as shown in Figure 7b). Similarly, participants using the map interface with location marker performed significantly better in path recall test than participants using map interface with directional arrow (F(1,28) = 4.86, p = 0.03). No other comparison was significant. Again lower values were better than the higher values here as the dependent measure was mean errors.

*Summary of results of incremental survey knowledge tests.* Our results show that participants using interfaces with only the directional arrow (in both map and video interfaces) performed the worst in incremental survey knowledge tests. This is consistent with our hypothesis. As the directional arrows did not encourage active processing of spatial information during their assisted navigation tasks, participants performed poorly in the orientation and path recall tests. However, the relative location updates (e.g., navigation circle and the location marker) were found to encourage the acquisition of incremental survey knowledge for the participants.

*6.2.2 Integrated Survey Knowledge Analysis.* We measured the integrated survey knowledge with the floor plan recall test.

*Floor plan recall test.* Fig 8 shows two sample floor plan drawn by our participants during the user study. For the floor plan recall test, we performed the same 2X2 ANOVA. The ANOVA analysis showed that the floor plan recall test score was significantly better for the map interfaces than the video



(a) (b)

**Figure 8: Sample floor plans drawn by participants. (a) A sample floor plan that shows high similarity with the actual floor plan (actual floor plan is shown in Figure 3a and 3b); (b) another sample that shows low similarity with the actual floor plan.**

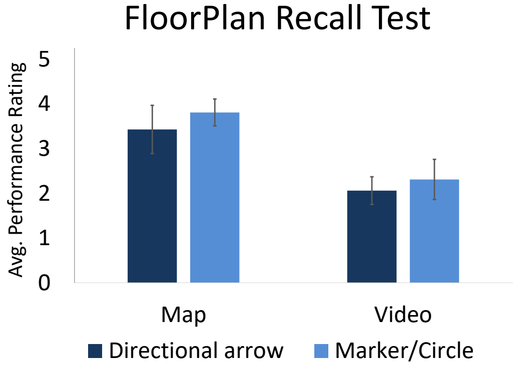


**Figure 9: Bar plot shows the mean of the floor plan test scores of all the variations of the interfaces. The range of the score for this test is 0-5.**

interfaces (F(1,28) = 22.71, $p < 0.01$) (Figure 9). However, there was no significant difference among the navigational cues, and the interaction was also not significant. A further planned t-test showed that the participants for the map interface with the location marker (M = 3.81, SD = 0.59) performed significantly better than the participants that used the video interface with navigation circle (M = 2.31, SD = 0.99), (F(1,28) = 12.36, $p < 0.01$). Similarly, participants for the map interface with the directional arrow (M = 3.43, SD = 1.08) performed significantly better than the participants that used the video interface with directional arrow (M = 2.06, SD = 0.62), (F(1,28) = 10.39, $p < 0.01$). No other effect was found significant.

*Summary of results of integrated survey knowledge tests.* The results of the floor plan recall test satisfied our initial expectation. The participants of the map interfaces could see the schematic floor plan of the environment during all the assisted navigation tasks, but the participants of the video interfaces never saw the floor plan through their interface. So, as we expected, the participants of the map interfaces would perform better than the participants of the video interfaces for this floor plan recall test and the results also supported our expectation.

### *6.2.3 Route Knowledge Analysis.*

To measure acquired route knowledge, we conducted a location recognition test and an unassisted navigation test. We will discuss the results of these two tests in this section.

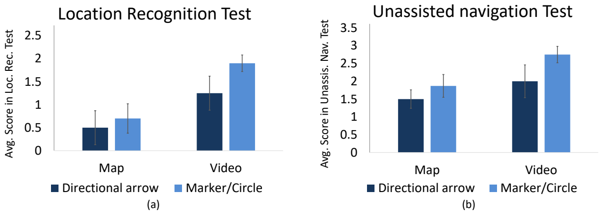


**Figure 10: Bar plot showing the mean of the location recognition test (a) and unassisted navigation test (b) scores of all the variations of the interfaces. The range of the score for the location recognition test is 0-2. The range of the score for the unassisted navigation test is 0-3**

*Location recognition test.* In this test, we showed the pictures of three locations to each participant and gave them three options to answer. We manually coded their responses for analysis. The response 'remember the place' is coded as 2, 'not sure, but remember the place to some extent' response is coded as 1 and 'do not remember the place' response is coded as 0. The mean score of all the participants in this test as shown in Figure 10a. A 2X2 ANOVA analysis shows that the location recognition scores yielded significant differences between the map and the video interfaces(F(1,28) = 17.59 $p < 0.01$). Further analysis showed that for interfaces with directional arrow, participants using the video interface (M = 1.50, SD = 0.75) performed significantly better than participants using the map interface (M = 0.50, SD = 0.75), (F(1,28) = 7.79 $p < 0.01$). Likewise, we also observed that participants using the video interface with navigation circle (M = 1.87, SD = 0.36) performed significantly better than participants using the map interface with location marker (M = 0.75, SD = 0.64) in this test (F(1,28) = 9.86 $p < 0.01$). No other effect was significant.

*Unassisted navigation test.* We measured the number of times the participants could reach their desired destination without any assistance. We coded the result as 0 when a participant failed to reach a desired destination and 1 when a participant successfully reached the desired destination. Each participant could get a maximum of 3 points and a minimum of 0 points in this test. The mean scores of all the participants in this test are shown in Figure 10b. A 2X2 ANOVA analysis shows that the unassisted navigation test scores yielded significant differences between map and video interfaces too (F(1,28) = 8.56 $p < 0.01$). We also observed significant differences for navigational cues (F(1,28) = 5.72 $p < 0.01$).

We performed the same planned pairwise t-tests for the unassisted navigation test. Participants using the video interface with navigation circle (M = 2.75, SD = 0.46) performed significantly better than those using the map interface with location marker (M = 1.87, SD = 0.64) (F(1,28) = 6.92, $p < 0.01$). Additionally, we observed that participants using the video interface with navigation circle (M = 2.75, SD = 0.46) performed significantly better than the participants using the video interface with directional arrow (M = 2.0, SD = 0.92), (F(1,28) = 5.09, p = 0.03). No other comparison was significant.

*Summary of results of route knowledge tests.* We found that the video interface with only navigation circle was the best for facilitating the acquisition of route knowledge among all the interfaces. This shows that active processing of spatial information from an egocentric perspective encouraged people to actively process their surroundings, which helps them acquire route knowledge. Although participants using interfaces with directional arrow successfully completed their tasks, turn-by-turn directions likely discouraged them to actively process spatial information. This lack of route knowledge learning was evident from the location recognition and unassisted navigation tests. Furthermore, the significant main effect of the interface variable in both location recognition test and unassisted navigation test shows that in general, video interfaces encourage learning of route knowledge acquisition more than map interfaces.

## 7 DISCUSSION

The goal of our study was to systematically investigate the design trade-offs of indoor navigation interfaces not only as a tool that helps people to navigate from one location to another but also as a tool that facilitates the incidental learning of spatial knowledge during navigation tasks. To this end, we designed and tested two types of interfaces (map and video) along with two types of navigational cues (directional arrow and relative location updates).

We found that although interfaces with only the directional arrow were suitable for simple navigation tasks, these interfaces failed to facilitate the acquisition of incidental spatial knowledge. Participants using the map and video interfaces with only directional arrows were not encouraged to actively process spatial information during assisted navigation tasks. As a result, participants completely relied on their interfaces to navigate and they learned the least spatial knowledge compared to the other groups. On the contrary, participants using interfaces with relative location updates (such as location marker or navigation circle), performed significantly better in survey and route knowledge tests. In our study, we did not find that these additional features had any negative effect on navigational performances. However, future research should more systematically test whether there is any trade-off between performance and learning. For example, in a more cognitively demanding situation (e.g., navigating in a busy city), active processing of spatial information may not be ideal. Further exploration should also be done in this direction to understand how multiple navigation cues can be combined in a single navigation application without deteriorating incidental spatial knowledge acquisition process.

Our results were consistent with previous literature, which showed that the process of acquiring spatial knowledge is not “automatic”. For example, in a 10-week long experiment, Ishikawa et al. [11] found that most participants made little to no improvement in acquiring spatial knowledge by naturally navigating in an environment. Our studies showed that even simple features may “nudge” people to actively process spatial information, in ways such that they can significantly promote the learning of spatial knowledge. We believe that these low-cost nudges can introduce “desirable difficulty” for users, and they are likely more cognitively compatible with the natural ways that people process spatial information.

Although the main focus of our study was navigation in indoor environments, in future we would like to validate our findings in outdoor navigation as well. We anticipate that our results will particularly be beneficial for users in new locations such as in a new city where users need to quickly acquire reliable spatial knowledge to “bootstrap” their spatial or non-spatial tasks. As discussed in the introduction, spatial knowledge not only helps users find their way to destinations but also allow them to integrate spatial knowledge to facilitate all aspects of a wide range of daily activities.

An interesting observation revealed during our user study was that participants aged above 40, who had more experiences using a paper map for navigation, preferred to check the navigation application intermittently and showed higher motivation to look around the environment in order to identify natural landmarks. On the other hand, younger participants tended to spend more time to follow the instructions given by the application with much less attention allocated to the environment. Perhaps younger participants were more adapted to reliance on technologies than our presumably more “natural” instinct in acquiring environmental knowledge. Further qualitative studies need to be designed to explore the effect of age and past experiences on their using digital navigation devices.

## 8 CONCLUSION

Spatial knowledge is one of the most fundamental knowledge that supports a wide range of activities, and thus is critical for humans to function well in different environments. Spatial knowledge is therefore essential not only in emergency rescue missions but also for everyday activities like task and route planning, social engagements, and urban planning and design. The main contribution of our study is to show that smart and thoughtful interface design can potentially help users acquire spatial knowledge incidentally without sacrificing their ability to perform point-to-point navigation. Perhaps a simple change of focus in existing interface designs can already lead to significant improvement in promoting incidental learning of spatial knowledge.

## 9 ACKNOWLEDGMENT

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