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# Investigating Four Navigation Aids for Supporting Navigator Performance and Independence in Virtual Reality

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**ABSTRACT**

Turn-by-turn navigation guidance is suggested to impair users' independent wayfinding in the physical world. However, whether this impairment issue also exists in a virtual environment is underexplored. We compare map-based and live view-based turn-by-turn navigation aids with two additional navigation aids, reference-based and orientation-based, designed to provide directional knowledge. The results of our within-subjects experiment indicate that turn-by-turn navigation aids performed worse in building spatial awareness than reference-based guidance in virtual reality. In unaided wayfinding, reference-based guidance helped users navigate most efficiently. Unexpectedly, orientation-based guidance yielded poor navigation performance, similar to the turn-by-turn navigation aids. We found that the key to skill impairment is navigators' tendency to rely on automated instructions. This suggests that turn-by-turn navigation aids need not be avoided, but rather that caution should be exercised to avoid the tendency of mindless instruction-following. Our qualitative findings also suggest the crucial roles of the navigation context and the suitability of the navigation aid for the context.

## 1. Introduction

Mobile navigation systems assist users in navigating to specific destinations. However, researchers have reported that the individuals using these systems become overly reliant on this type of guidance, resulting in a failure to acquire spatial knowledge while navigating. Specifically, Ishikawa et al. (2008) and Münzer, Zimmer, Schwalm, Baus, and Aslan et al. (2006) both reported that users of mobile navigation systems do not acquire the knowledge required to build cognitive maps and process information pertaining to their surroundings. This is because navigators have been found to easily become overly-reliant on turn-by-turn instructions, causing their navigation to often become "mindless" (Parush et al., 2007). As a result, despite the lower cognitive workload turn-by-turn instructions demand from navigators because of this tendency, navigators tend to fail to acquire the spatial knowledge required for independent navigation along the same route in the future when no aid is provided (Ishikawa et al., 2008). This decline in independent-wayfinding skills and the danger that it may lead to has been discussed extensively in the literature. For example, because the accuracy of spatial information provided by navigation systems depends on the stability of the GPS signal, network signal, and electronic compass in the relevant device, in the event that one of these systems fails, the user becomes unable to proceed, as they lack the spatial information required for self-navigation (e.g., Aslan et al., 2006; Ishikawa et al., 2008; Schwering et al., 2017; Wakamiya et al., 2016).

Over the past years, numerous studies and modern systems have been developed to help navigators acquire spatial knowledge during the navigation process (Parush et al., 2007; Wen et al., 2014). For example, state-of-the-art mobile navigation systems, such as Google Maps Navigation, allow users to examine the route super-imposed over street maps from a bird's-eye view, which helps them to acquire survey knowledge (Golledge et al., 1995). Augmented-reality (AR) systems have also been incorporated into navigation systems such as Google Maps and Blippar AR City to provide live-views of street scenes with route instructions (Chung et al., 2016; Walther-Franks & Malaka, 2008), with the aim of prompting users to pay more attention to the environment and in so doing encode more environmental information en route.

Differing from the physical environment, virtual reality (VR) is envisioned to provide numerous types of virtual worlds for users to navigate through. Despite the fact that a navigator may not face the challenge of losing their navigation aid as they would in the physical world since in a virtual world a navigation aid can be assumed to be available permanently, supporting spatial learning to facilitate independent navigation arguably has benefits. That is, being able to independently navigate without a navigation aid could reduce the navigator's need to frequently switch his or her visual attention back and forth between the environment

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and the navigation aid (Giannopoulos et al., 2015), thereby decreasing their burden in navigation and increasing the feeling of immersion (Bowman & McMahan, 2007; Schnall et al., 2012). However, it is unclear whether turn-by-turn navigation aids in VR would impair the navigator's acquisition of spatial knowledge and the development of skills required for independent wayfinding in VR as it can in the physical world. By the same token, the extent to which improved turn-by-turn navigation aids, that is, incorporating them with maps and live views of street scenes, would solve the issue remains unknown. We regard these as important questions to answer due to the increasing popularity of on line virtual worlds and research attention on simulating movement in the physical world in VR. In our study, we aim to determine whether turn-by-turn navigation aids impair the acquisition of spatial knowledge and the development of skills required for independent wayfinding in a virtual environment.

In doing so, we examine whether turn-by-turn systems equipped with maps (Map-based turn-by-turn) and live views (Liveview-based turn-by-turn), respectively, would cause the impairment of spatial skills for independent wayfinding and of spatial knowledge acquisition. We compared these two kinds of navigation aids with two other kinds of navigation aids that provide users with directional spatial knowledge about the environment and the destination, namely, global orientation information (Orientation-Based) and relative location information with a global landmark (Reference-Based), respectively. We conducted a within-subjects experiment with 26 users navigating in VR and compared these four navigation aids in terms of users' navigation performances in aided navigation and in subsequent unaided (or independent) navigation as well as two spatial knowledge tests. In addition to the comparisons, we sought to understand, from the navigator's perspective, which kind of navigation aids they preferred to use, when they would prefer one over the others, and the reasons for their preferences. To sum up, the main contributions of this article are as follows:

- We show that the key to the impairment of the skill for the independent navigation task is not the provision of turn-by-turn navigation aids per se but the navigator's tendency to rely on automated instructions.
- We show that while two turn-by-turn navigation aids made users consult more navigation aids in independent navigation tasks and build poorer spatial awareness, the Orientation-Based navigation aid also led to poor navigation performance in subsequent independent navigation tasks.
- We show that while the Reference-Based navigation aid led to the least efficient navigation in aided navigation, it performed the best in all aspects of independent navigation tasks.
- The qualitative findings provide insight into the pros and cons of each of the navigation aids and that they are favored in different contexts depending on the trip characteristics, trip purpose, and the navigator's familiarity with the environment, suggesting that it is important to consider the suitability of the navigation aid for the navigation context.

## 2. Related works

### 2.1. Acquisition of spatial knowledge

Spatial knowledge is an essential aspect of wayfinding. Human spatial knowledge can be divided into three components: landmark knowledge, route knowledge, and survey knowledge (Siegel & White, 1975). Landmark knowledge includes salient places in the environment; route knowledge comprises a sequence of points; and survey knowledge is a configurational concept of landmarks and routes within the environment similar to a map (Siegel & White, 1975).

Most people use either a survey strategy or route strategy to perform wayfinding tasks (Lawton, 1996). Survey strategies consider allocentric relations in the environment based mainly on survey knowledge. When people think in cardinal directions or Euclidean positions between landmarks, they are using survey strategies for navigation (Prestopnik & Roskos-ewoldsen, 2000). Route strategies are based on an egocentric frame of reference. Previous studies have reported that high-performing navigators plan routes using a survey method, whereas low-performing navigators use a routing strategy. Golledge et al. (1995) reported that after an equivalent number of learning trials, map learning yielded fewer errors than did route learning, even in the estimation of distances and angles. Numerous researchers have emphasized the importance of survey knowledge for effective navigation, based on an understanding of the spatial relationships between elements in the environment as well as the navigator's own relative location (Siegel & White, 1975). Survey knowledge also enhances the user's ability to create novel routes (Thorndyke & Hayes-Roth, 1982), which increases the likelihood of success when tasked with unaided (i.e., independent) wayfinding (Montello, 1998).

Researchers have previously compared the effectiveness of navigation approaches in promoting the learning of spatial knowledge. Münzer et al. (2006) compared paper maps with three electronic navigation modes: visual + context, auditory + context, and auditory only. They reported no significant differences between the three modes in terms of spatial knowledge acquisition, due to the fact that none of the electronic navigation instructions required the active encoding of spatial information. They also reported that the users of electronic navigation devices generally show good route knowledge and poor survey knowledge, whereas the users of paper maps show relatively good survey knowledge and nearly perfect route knowledge. Huang et al. (2012) observed equally poor results in the acquisition of spatial knowledge using a mobile map, AR, and voice-only navigation guidance. Ishikawa et al. (2008) reported that map-based turn-by-turn GPS navigation systems hindered the acquisition of spatial knowledge, compared to paper maps, with the result that subjects required more time to reach their destination. The users of turn-by-turn GPS navigation systems tended to take circuitous routes, make many unplanned stops, and make more grievous errors in direction, and were unable to produce accurate sketch maps of the region of interest. All of these results can be attributed to a lack of survey knowledge. Given the literature, it might be reasonable to assume that similar results from these outdoor studies can also be observed in the navigation in virtual worlds. However, this issue has not yet been explored.

A number of researchers have sought to find ways to facilitate the acquisition of spatial knowledge while using navigation aids. Parush et al. (2007) attempted to reduce reliance on automated wayfinding systems by designing a navigation interface that requires the user to request an update of their position, rather than having it update automatically. Their system also prompted users with an orientation quiz while wayfinding. These schemes were shown to outperform conventional GPS-based turn-by-turn systems in terms of survey knowledge acquisition. But again, whether supporting the acquisition of spatial knowledge of the virtual world during navigation aids would also enhance navigators' actual knowledge of the virtual world as well as their subsequent independent navigation remains unclear.

### 2.2. Navigation aids

Numerous researchers have sought to improve outdoor navigation performance. One approach is to focus on the output mode of the navigation aids in an effort to move beyond visual-based systems. Accordingly, researchers have developed systems based on voice commands (e.g., Huang et al., 2012; Rehrl et al., 2012; Streeter et al., 1985), tactile stimulation (e.g., Pielot et al., 2012; Velázquez et al., 2018), quadcopter projectors (e.g., Knierim et al., 2018), and even X-rays that enable users to look through walls (Dey et al., 2011). Most of this research has focused on technical aspects rather than the cognitive processes involved in acquiring spatial knowledge. Navigation systems for pedestrians have drawn considerable attention. Rehrl et al. (2012) compared the efficiency of three turn-by-turn instruction modes: digital maps, LiveView-Based navigation, and voice-only instruction. Overall, LiveView-Based navigation proved the least effective in terms of task completion time, the number of stops, and cognitive load.

Researchers have reported that including orientation information in wayfinding instructions is an effective approach to linking the destination to the navigator's current location and facilitating the acquisition of survey knowledge (Dey et al., 2018). In a comparison of map-based (allocentric) and video-based (egocentric) interfaces, Dey et al. (2018) employed three navigation cues: directional arrows (turn-by-turn), location markers, and navigation circles (orientation information). They found that providing only turn-by-turn directions failed to facilitate the acquisition of spatial knowledge. Overall, map-based interfaces were better for acquiring survey knowledge, whereas video-based interfaces were better for acquiring route knowledge. They found that participants did not take a significantly longer time to complete the assisted navigation task compared to turn-by-turn cues. Video interfaces also were proved more effective than map interfaces in subsequent unassisted navigation tasks. Taken together, these findings indicate that navigation systems relying on turn-by-turn instructions tend to hinder the acquisition of spatial knowledge (particularly survey knowledge) during wayfinding.

In addition to outdoor navigation systems, we note that indoor navigation has also drawn much attention from researchers. Extensive reviews of indoor navigation systems can be found in Davidson and Piché (2017), Fallah et al. (2013), and Kunhoth et al. (2020). Overall, due to the fact that GPS signals cannot be received indoors and that indoor navigation typically requires high positioning accuracy, many of these studies have focused on developing technology for indoor positioning, which can be classified into three types: communication technology (Wi-Fi, Bluetooth, RFID, etc.), computer vision, and pedestrian dead reckoning (PDR) (Davidson & Piché, 2017; Fallah et al., 2013; Kunhoth et al., 2020). Another main direction is representing indoor environment, such as 3 D modeling (Dong et al., 2015) and map construction (Gao et al., 2017; Liu et al., 2017; Pradhan et al., 2018). Most likely due to the fact that indoor navigation typically considers only pedestrian navigation, transportation methods and safety issues are of less concern in indoor navigation than in outdoor navigation. This likely also makes over-reliance on and over-attention to navigation aids less discussed in the context of indoor navigation. Despite these differences, similar navigation techniques have been used in indoor navigation aids, such as an AR-based approaches (Gerstweiler et al., 2015; Rajeev et al., 2019) and an image-based approach (Dong et al., 2015; Niu et al., 2019).

As in the outdoor and indoor navigation aid research for the physical world, navigation aids in VR have been recently explored by some researchers for supporting wayfinding (e.g., Razzaque et al., 2002; Wu & Popescu, 2018) and exploration (e.g., Wang et al., 2019); other researchers have used VR to study spatial knowledge learning (Richardson et al., 1999; Savino et al., 2019). Yet, the comparison of the effectiveness of navigation aids in supporting subsequent independent navigation in VR has been underexplored.

To fill the research gap, in the current study, we examined whether modern state-of-the-art navigation aids are subject to the same limitations in VR as they are in the context of outdoor navigation in the physical world. Specifically, we evaluated (1) a Map-Based Turn-by-Turn system, which allows users to examine a complete map during and even before wayfinding, and (2) an LiveView-Based Turn-by-Turn navigation system, which prompts users to engage with the surrounding environment, against two navigation aids designed to increase the navigator's spatial knowledge of the virtual world.Below we introduce the four navigation aids under investigation and the experiment setup.

## 3. Methodology

### 3.1. Within-subject experiment

From the outset, we deemed it necessary to conduct a within-subjects experiment so that we could obtain feedback from participants on all of the four navigation aids. This is because we hoped to understand how navigators experienced and felt about the assistance from each of these aids during aided navigation as well as afterwards, that is, needing to independently navigate on their own without any aid. This allowed them to reflect on the differences between the aids and the pros and cons of each navigation aid. In the following, we introduce the setup of the study environment.

### 3.2. Virtual City

We built a virtual city using the Unity game engine. The street map was based on open street data from a city in the real world. The buildings were roughly similar to the original buildings in terms of style; however, we eliminated salient and unique landmarks to prevent interference with subsequent navigation tasks. Note that generic landmarks were retained for simulations using the Reference-Based navigation aid. We included coffee shops and convenience stores that were easily recognizable to serve as destinations. Note that the destinations were located in small lanes to make them less noticeable on major streets. Participants wore VR headsets (HTC VIVE pro) while exploring the virtual world. The right VR hand controller was used to turn a virtual mobile phone on and off and to control the navigator's movement in the virtual world. The left hand controller consisted of a beam pointer that could be used to interact with the buttons and the mobile phone in the virtual environment. The walking speed of the navigator was fixed to avoid interruptions from external factors and to maintain inter-subject consistency during movement.

### 3.3. Participants

With a within-subjects experiment setup, we recruited 26 participants (12 men and 14 women) ranging in age from 20 to 55 years old. Twenty-two participants were students aged from 20 to 25 years old. The other four participants were non-students. When signing up for the study, the participants completed the Santa Barbara Sense of direction Scale (SBSOD; (Hegarty et al., 2002)) to measure their sense of direction, and rated their familiarity with mobile navigation systems using a Likert-scale, ranging from (1) "very unfamiliar" to (5) "very familiar." The aim in participant selection was to balance participants' sense of direction scores with their familiarity with mobile navigation systems.

### 3.4. Experiment design

Our within-subjects design required that each participant to experience four navigation trials, each in which they navigated to a designated destination using one of the four navigation aids. We established two starting points leading to four different destinations (i.e., routes), as shown in Figure 1. The four routes varied from easy (three turns) to difficult (six turns). Note that the routes to specific shops were determined by the Virtual City system using the shortest-path rule. The length of each route was equivalent within


Figure 1. Map of the virtual study area showing four wayfinding-task routes color coded by complexity level. (Route 1 has 3 turns; route 2 has 4 turns; route 3 has 5 turns; route 4 has 6 turns).

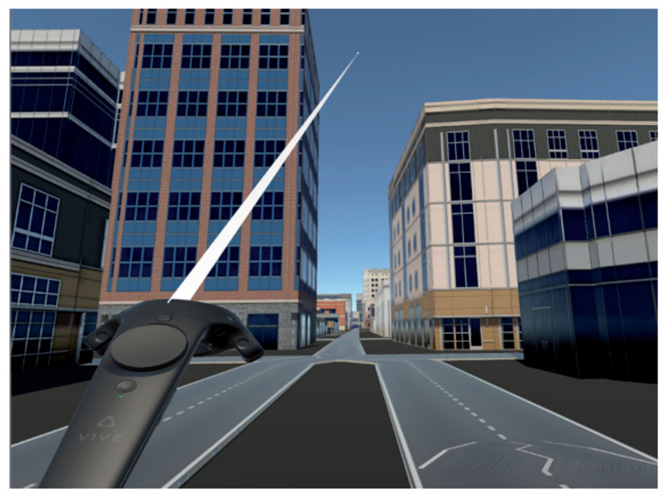

Figure 2. The virtual city environment. Participants use hand controllers to navigate.

500–600 meters. (Figure 2) There are a total of 24 possible orders among the four navigation aids and among the four routes, respectively. We randomly matched these two sets of 24 orders. This resulted in 24 pairs of navigation-aid order and route order; we then randomly assigned each pair to a participant. Consequently, the order among the four navigation aids was counterbalanced; each of the possible orders of navigation aid was experienced by at least one participant. Each navigation trial was divided into two navigation tasks. In the first task, *the aided navigation task*, the assigned navigation aid was offered the entire time, and in the second task, emphthe unaided navigation task, the assigned navigation aid was not offered upfront but was available if needed. In both tasks, participants navigated to the same destination; that is, the routes in the aided and the subsequent unaided navigation tasks were the same. Specifically, as shown in Figure 3, the participant was firstly instructed to follow the guidance offered by the navigation aid in the first navigation task (Figure 4). After arriving the destination, the participant was then reset to the same starting point and instructed to use the hand controller to point to the destination (*pointing*

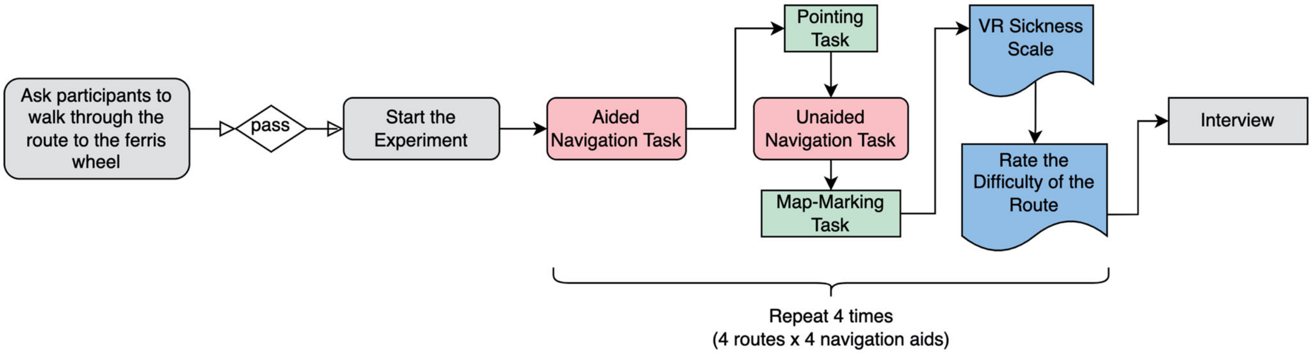


Figure 3. The flowchart of the experiment procedure.

Figure 4. Screenshot of map-marking task. Participants have to select the position of the destination landmark on the street map.


Figure 5. Screenshot of pointing task. Participants have to point the direction of the destination landmark.

*task*, as shown in Figure 5). After the pointing task, the participant performed the second navigation task. In this task, the navigation aid was not offered upfront; instead, they were told that they should try their best to navigate to the destination on their own; however, when they felt stuck or lost and needed assistance, they were allowed to consult the navigation aid via the virtual mobile phone. After completing it, the participant was instructed to mark the destination at which they had just arrived on a street map of the virtual city from a bird's eye view (*map-marking task*, as shown in Figure 4). The performance metrics for both navigation tasks were travel time and distance travelled. In the second unaided task, we measured participants' assistance-seeking, i.e., the number of times and the time spent consulting the phones. Distance error was estimated from the results of the map-marking task, and angular error was estimated in the pointing task.

## 4. Four types of navigation aids

We designed four navigation aids for this experiment. The first two aids were turn-by-turn: Map-Based Turn-by-Turn and LiveView-Based Turn-by-Turn. Both aids provided turn-by-turn instructions en route based on the shortest-route policy typical of commercial navigation systems. They also provided automated route re-planning, wherein a new route was planned if the user deviated from the predefined path. The second two navigation aids were non-turn-by-turn: Orientation-Based and Reference-Based. These aids did not indicate a specific route to the destination; however, they provided other navigation cues (discussed later). All of these modes automatically updated the navigator's present location.

### 4.1. Map-based turn-by-Turn

As shown in Figure 6(a), the Map-Based Turn-by-Turn interface was similar to that used for well-known mobile navigation applications, with the planned route indicated by a blue line, the current location of the user indicated by a blue point, and the navigator's orientation indicated by a blue beam. Note that the orientation of the map was always aligned with the orientation of the navigator. The navigator was allowed to check the entire route by moving the map using a hand controller and to center the map to their own current location at any point simply by pressing the" My Location" icon.

### 4.2. Liveview-based turn-by-Turn

The LiveView-Based Turn-by-Turn navigation aid was inspired by existing AR-Based navigation systems (e.g., Blippar AR City[1] https://www.blippar.com/blog/2017/11/06/welcome-ar-city-future-maps-and-navigation, Wikitude Navigation[2] https://www.wikitude.com/showcase/wikitude-navigation/, and Google Map AR Navigation[3] https://techcrunch.com/2020/10/01/google-maps-gets-improved-live-view-ar-directions/) that provide live-views of street scenes during navigation. The interface used in the experiment mimicked

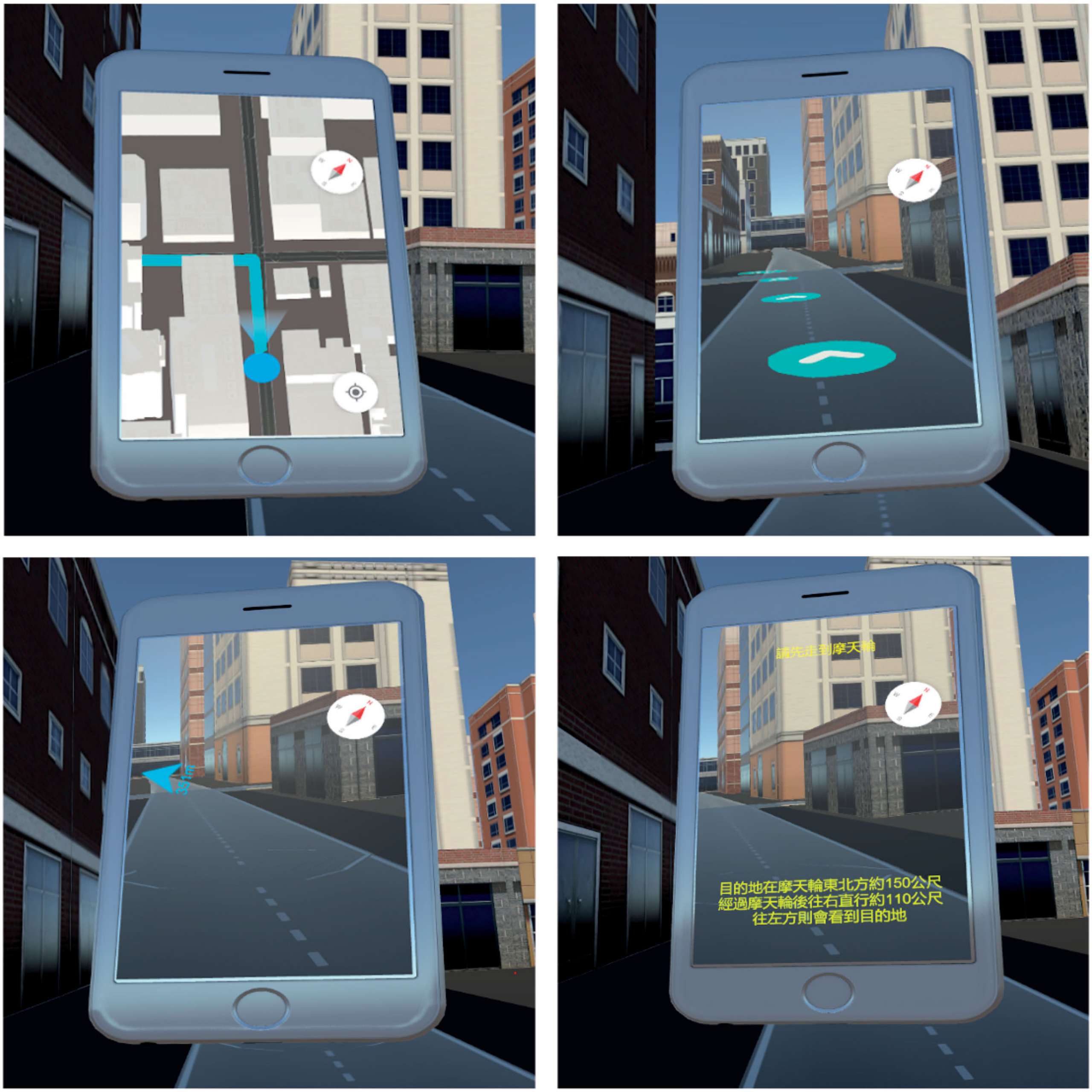


**Figure 6.** The four focal navigation-guidance modes. (a) Map-Based Turn-by-Turn (b) LiveView-Based Turn-by-Turn (c) Orientation-Based (d) Reference-Based.

the AR Live View feature on Google Maps, in which the navigator views their route as a moving blue arrow on the ground through the virtual mobile phone's camera view. The arrow was overlaid on the street on the camera view. Projecting street scenes onto the navigation interface presumably prompts the navigators to match the live-view of the street scene to the street scene they can see in the virtual environment.

### 4.3. Orientation-based

The inclusion of the Orientation-Based navigation aid was inspired by Dey et al. (2018), in which it was posited that global orientation information could help the navigator to learn about the directional relation between the navigator's current location and the destination. This type of directional information is a key element of survey knowledge. As shown in Figure 6(c), at the top of the interface there was a blue arrow, which always pointed toward the destination, with a label next to it indicating the absolute distance (in meters) between the navigator's current location and the destination. This aid did not provide turn-by-turn instructions; instead, we expected the navigator to incidentally acquire spatial information by making efforts to find a route on their own toward the destination, as posited by Dey et al. (2018). Given that it did not allow following turn-by-turn instructions and that the navigator needed to find their own way, we assumed that this approach would outperform both turn-by-turn navigation aids in the unaided navigation task and spatial knowledge task.

### 4.4. Reference-based

The inclusion of the Reference-Based navigation aid was inspired by previous research on the use of global landmarks to facilitate navigation (Steck & Mallot, 1998). This approach relates the location of the destination to a reference with which the navigator is already familiar. The navigator needs to make sense of how to navigate to the destination using the reference as an anchor. The reference used in these experiments was a Ferris wheel in the center in the virtual city (see Figure 2). To make participants familiar with the reference in advance, we provided them with videos demonstrating how to navigate from two starting points, which were the same in the experiment, to the Ferris wheel prior to the experiment. Note that the video did not show participants the navigation aid, but rather only how to move to the reference point. The interface for this navigation aid comprised a textual description of the navigator's current location relative to the reference destination (as shown in Figure 6(d)), with a short verbal description (e.g., "The destination is 190 meters southwest of the Ferris wheel. Turn right at the first intersection after the Ferris wheel. Go straight for 110 meters. The destination is on the right-hand side"). Based on the fact that this scheme provides relational information, we assumed it would outperform the two turn-by-turn navigation aids in the unaided navigation task and spatial knowledge task.

### 4.5. Procedure

As mentioned earlier, none of the participants had prior experience with the virtual city; therefore, we asked them to familiarize themselves with the routes to the reference landmark (Ferris wheel) by repeatedly viewing the videos we provided them with and rehearsing prior to the experiment. After the participants entered the research lab, the research team outlined the research objectives and experiment procedure. The participants were then shown a video tutorial of the four navigation aids and given the opportunity to practice moving through the virtual city. Then they were asked to demonstrate how to navigate to the Ferris wheel following the routes shown in the videos. All participants demonstrated that they had indeed learned these routes by successfully and smoothly navigating to and arriving at the destination.

After the demonstration, the participants started the four trials. Note that they did not know the order of the navigation aids in advance. As a reminder, each participant ran through four trials. In each trial, the participants performed two navigation tasks, first aided and then unaided. After each trial, the participants took a small break. Upon completion of each trial, the participants rated the difficulty of the unaided navigation task and the difficulty of each route using a Likert-scale ranging from (1)" very easy" to (5)" very difficult." They were then given a three-minute break and asked to fill out a VR sickness scale (Kim et al., 2018). Upon completion of all four trials, they were invited to participate in an optional interview to relate their experiences in using the navigation aids. We asked them to reflect on the pros and cons of the four aids, to list their likes and dislikes, and to describe navigation situations where they believed the navigation aids would be suitable or unsuitable. Each interview lasted between 15 to 25 minutes. After the interviews, the participants were offered compensation of NTD 400 (roughly 13.6 USD). The study was approved by the Research Ethics Committee for Human Subject Protection, National Tsing Hua University.

### 4.6. Data analysis

Our study employed a within-subjects design, and each subject underwent repeated measures. This made it necessary to consider how the order of the routes might influence the results. There was also the possibility that an individual's sense of direction and the complexity of the routes would affect their navigation performance. We therefore employed a mixed-effects linear regression model to identify the main effects of the navigation aids. Specifically, we ran the regression in the R software, which allowed us to examine the pairwise contrast between levels in a categorical variable (e.g., navigation aids) by setting a navigation aid as the reference level. As a result, we were able to observe pairwise comparisons between navigation aids. In addition to the main effect of the navigation aid, we also included effects of task order, route, and SBSOD score to account for the variances they caused. Finally, given that each observation from a participant was not independent due to the repeated-measures design, the mixed-effects model allowed us to include a random effect of participants to account for their individual variances.

Our specific results are described in the following subsections. For the sake of simplicity, the quantitative results are referred to as follows: ORTN (Orientation-Based), REF (Reference-Based), LIVE (LiveView-Based Turn-by-Turn), and MAP (Map-Based Turn-by-Turn).

We analyzed participants' interview transcripts using affinity diagramming (Kawakita, 1991) to obtain qualitative findings. In building the affinity diagram, we employed an iterative process of bottom-up grouping and labeling to identify high-level themes regarding participants' experiences, concerns, and reflections on the four navigation aids. This qualitative analysis approach has been used in mixed-methods experiments that aim to use qualitative findings to provide insights and explanations for quantitative results (e.g., Hsieh et al. (2020)). Several themes emerged from the analysis, including the pros and cons of each navigation aid for aided and unaided navigation tasks, spatial knowledge acquisition, and the influence of context. We report these qualitative findings separately from the quantitative results.

## 5. Quantitative results

### 5.1. Aided navigation task

Here, we will first look at participants' performance in the aided navigation tasks; specifically, participants navigated to a given destination by following the navigation aid.

We first examined the performance of participants in navigating to their destinations using a navigation aid. As shown in Figure 7, the time spent navigating to the destination using REF (M = 123.1, SD = 34.1) significantly exceeded that of the other navigation aids (MAP: M = 105.6, SD = 36.5, $t(69)$ = 2.8, $p = 0.005$; LIVE:M = 95.2, SD = 18.4, $t(69)$ = 4.7, $p < 0.001$; ORTN: M = 98.5, SD = 19.1, $t(69)$ = 3.8, $p < 0.001$). Note that there were no significant differences among any of the other aids in terms of travel time. The distance traveled on the way to the destination using REF (M = 645.2, SD = 102.3) was also significantly longer than that of the other navigation aids (MAP: M = 583.1, SD = 134.6, $t(69)$ = 3.9, $p < 0.001$; LIVE: M = 551.5, SD = 53.7, $t(69)$ = 5.5, $p < 0.001$; ORTN: M = 575.5, SD = 75.6, $t(69)$ = 3.8, $p < 0.001$), as shown in Figure 8. This means that REF was the least efficient approach among all the navigation aids in helping participants arrive at the destination in the aided navigation task in terms of speed and distance traveled. The other three navigation aids achieved efficiency similar to each other.

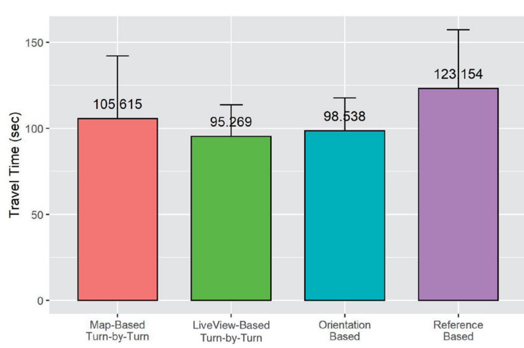


**Figure 7.** Mean and standard deviation of travel time in the aided navigation task.

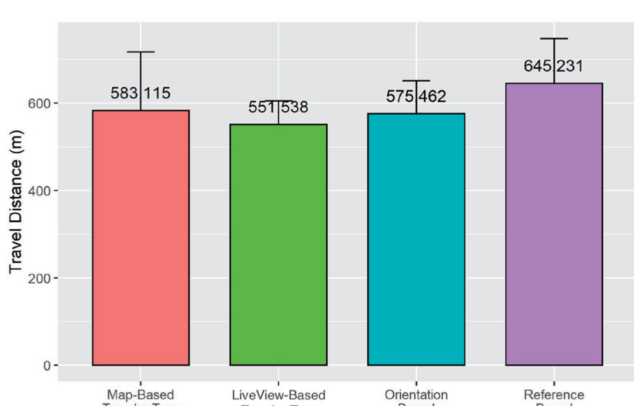


**Figure 8.** Mean and standard deviation of travel distance in the aided navigation task.

### 5.2. Unaided navigation task

Below we outline the results of participants' performances in the unaided navigation task and knowledge tests.

#### 5.2.1. Travel time and travel distance

As shown in Figure 9, the participants spent less time independently navigating to the destination using REF (M = 93.7, SD = 22.2) than they did after using the other three navigation aids. However, probably due to the small sample size, statistically significant differences were observed only between REF and ORTN (ORTN: M = 124.8, SD = 67.0, $t(69)$ = 2.6, $p = 0.01$). The other differences were only marginal (MAP: M = 113.7, SD = 50.4, $t(69)$ = 1.7, $p = 0.09$; LIVE: M = 116.1, SD = 18.4, $t(69)$ = 1.9, $p = 0.06$). Nevertheless, it is noteworthy that REF was the only navigation aid with which participants spent less time in the independent navigation task than they did in the aided navigation task. Furthermore, it was even as fast as when they were using turn-by-turn navigation aids in the aided navigation. This result suggests that the Reference-Based approach enabled participants to acquire sufficient spatial knowledge for smoothly navigating to the destination by themselves without much external assistance, with the same efficiency as using a turn-by-turn navigation aid. We observed no other significant differences among the other navigation aids in terms of travel time.

Similarly, as shown in Figure 10, the participants also traveled the longest distance navigating to the destination in the independent navigation task using ORTN (M = 773.3, SD = 416.3). The difference between ORTN and MAP (M = 639.8, SD = 140.9) and that between ORTN and REF (M = 614.1, SD = 134.6) were both statistically significant (vs. MAP: $t(69)$ = 2.0, $p = 0.04$; vs. REF: $t(69)$ = 2.3, $p = 0.02$), respectively. The difference between ORTN and LIVE was not statistically significant (M = 669.3, SD = 160.7, $t(69)$ = 1.4, $p = 0.14$). None of the other pairwise differences were statistically significant either. Again, REF was the only mode in which participants traveled shorter distances in the independent navigation task than they did with the navigation aid. In contrast, the ORTN mode resulted in the longest average travel distance, approximately 34%

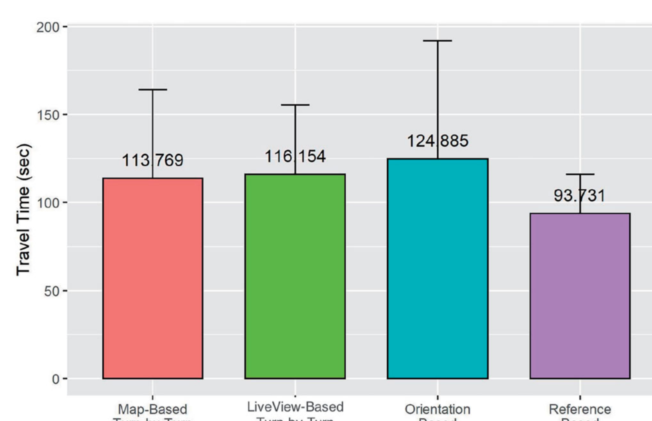


**Figure 9.** Mean and standard deviation of travel time in the unaided navigation task.

longer than the aided navigation task. This poor performance of ORTN, that is, the longest average travel time and distance in the independent unaided navigation task, was somewhat unexpected, since ORTN was also intended to help participants acquire directional spatial knowledge. However, we observed that this was because participants using this mode also had a tendency to follow the orientation arrow without encoding the route knowledge necessary to repeat the route later, making them unable to recall which route to take to efficiently navigate to the destination when no aid was present. This implies that the key to the impairment of the skill for the independent navigation task is not the provision of turn-by-turn navigation aids per se, but the navigators' tendency to rely on automated instructions, causing the ORTN approach to also lead to poor independent navigation performance (Table 1, Figure 11).

#### 5.2.2. Assistance seeking

We recorded the number of times the participants consulted their phones for assistance in the independent navigation task as well as the amount of time they spent doing so. As shown in Figure 12, participants seldom had to seek assistance in the independent navigation task after completing the aided navigation task using REF (Count: M = 0.6, SD = 1.2), which was far less than when using the other navigation aids (MAP: M = 2.4, SD = 3.3; LIVE: M = 2.4, SD = 3.7; ORTN: M = 1.7, SD = 2.6). The differences between REF and the two turn-by-turn navigation aids were both statistically significant (vs. MAP: $t(69) = 2.6$, $p = 0.008$; vs. LIVE: $t(69) = 2.8$, $p = 0.006$). No other significant differences were observed. Note also that in the REF condition, only six participants sought assistance from the phones. They also spent little time consulting their phones (1.46 seconds), which was statistically significantly shorter than when the navigation aids used were turn-by-turn aids vs. MAP: M = 6.0, SD = 9.5, $t(69) = 2.3$, $p = 0.02$; vs. LIVE: M = 7.4, SD = 10.4, $t(69) = 3.1$, $p = 0.002$). No statistically significant differences were observed in other pairwise comparisons. Again, our results confirm that REF was the most effective navigation aid in terms of teaching users how to navigate independently without assistance.

### 5.3. Survey knowledge tests

#### 5.3.1. Orientation estimation: Pointing task

As Figure 13 shows, REF and MAP were comparable in regard to participants' accuracy in the pointing task. This result confirms that providing participants with relational and survey spatial knowledge made them able to point to more accurate directions (i.e., less angle error). On the other hand, Figure 13 shows that LIVE seemed to achieve the largest angle error. However, due to the high degree of variance in the pointing tasks, the differences between LIVE and the other modes were only marginally statistically significant

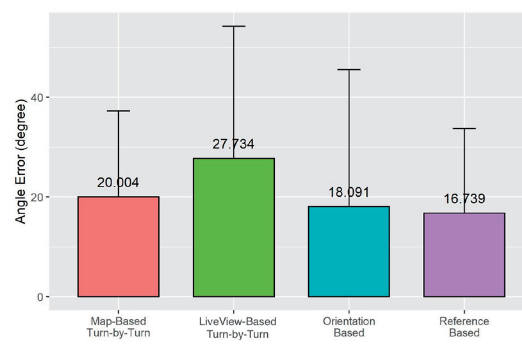


**Figure 11.** Mean and standard deviation of assistance seeking time in the unaided navigation task.

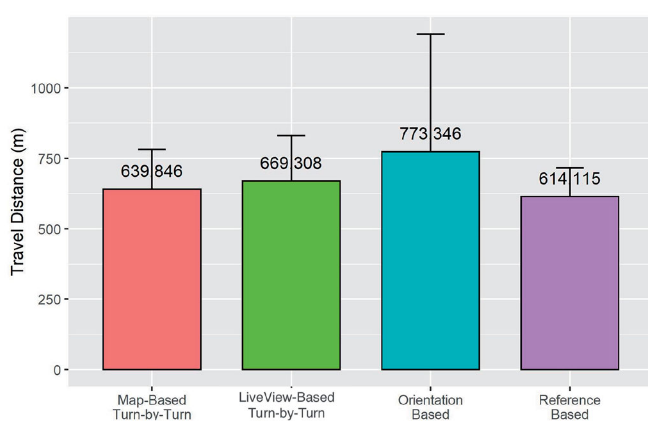


**Figure 10.** Mean and standard deviation of travel distance in the unaided navigation task.

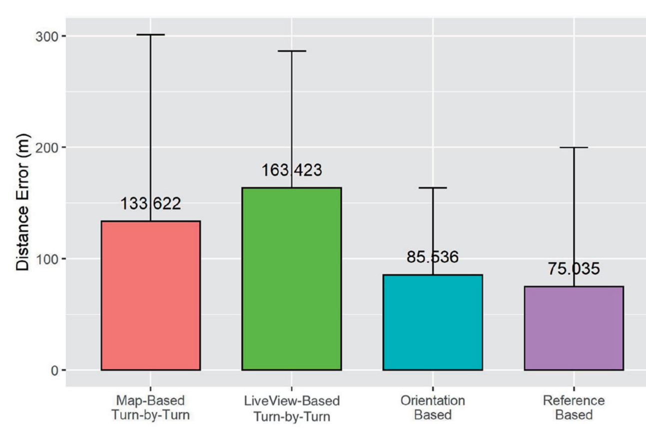


**Figure 12.** Mean and standard deviation of number of assistance seeking in the unaided navigation task.

**Table 1.** Means (and standard deviations) for each variable by participants in the four groups of independent-wayfinding task.

| | Map | LiveView | Orientation-Based | Reference-Based |
|---|---|---|---|---|
| Time(sec) | M = 113.8 (SD = 50.4) | M = 116.2 (SD = 39.3) | M = 124.9 (SD = 67.0) | M = 93.7 (SD = 22.2) |
| Distance(m) | M = 639.8 (SD = 140.9) | M = 669.3 (SD = 160.7) | M = 773.3 (SD = 416.3) | M = 614.1 (SD = 101.3) |
| Number of Assistance Seeking | M = 2.5 (SD = 3.3) | M = 2.5 (SD = 3.7) | M = 1.8 (SD = 2.6) | M = 0.6 (SD = 1.2) |
| Assistance Seeking Time(sec) | M = 6.0 (SD = 9.5) | M = 7.4 (SD = 10.4) | M = 4.5 (SD = 7.1) | M = 1.5 (SD = 3.2) |
| Difficulty | M = 2.9 (SD = 1.2) | M = 3.2 (SD = 1.2) | M = 3.1 (SD = 1.3) | M = 2.2 (SD = 1.0) |

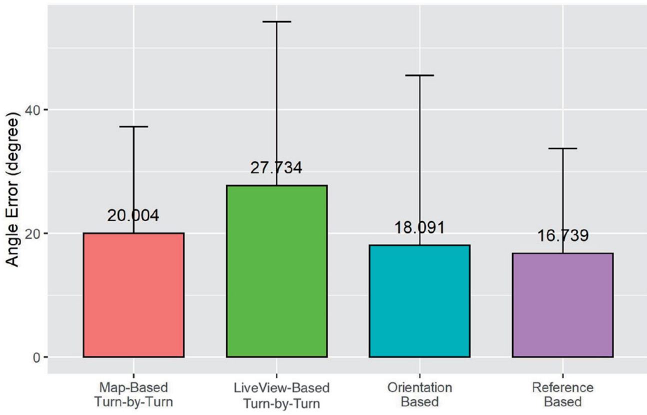


**Figure 13.** Mean and standard deviation of angle errors from the pointing task.

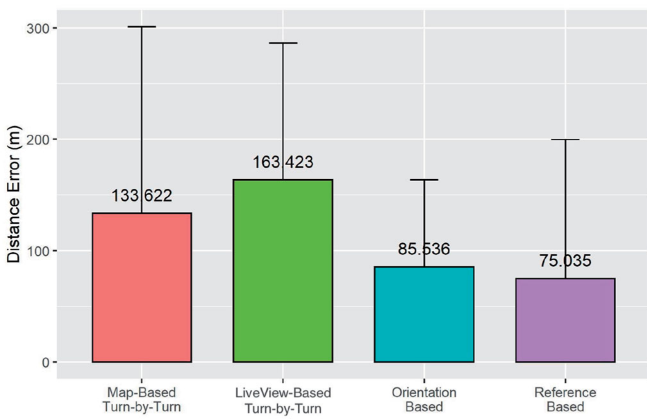


**Figure 14.** Mean and standard deviation of distance errors in the the map-marking task.

(MAP: $t(69) = 1.5$, $p = 0.11$; ORTN: $t(69) = 1.8$, $p = 0.07$; REF: $t(69) = 1.6$, $p = 0.11$).

### 5.3.2. Location estimation: Map-marking task

In the map-marking task, participants marked their current position on a bird's eye-view street map after arriving at the destination. Figure 14 shows that ORTN and REF led to greater map-marking accuracy (i.e., less distance error) than the two turn-by-turn navigation aids. The differences between REF (M = 75.0, SD = 124.7) and the two turn-by-turn navigation aids were both statistically significant (vs. MAP: M = 133.6, SD = 167.3, $t(69) = 2.6$, $p = 0.01$; vs. LIVE: M = 163.4, SD = 122.8, $t(69) = 3.6$, $p < 0.001$). The difference between ORTN and LIVE was also statistically significant ($t(69) = 3.0$, $p = 0.003$); however, the difference between LIVE and MAP was only marginally statistically significant ($t(69) = 1.5$, $p = 0.11$). These results suggest that REF and ORTN enabled participants to locate their destinations with a high degree of accuracy. Note that the Map-Based Turn-by-Turn instruction allowed participants to view the location of the destination; however, it did not help them in the map-marking task. The LiveView-Based Turn-by-Turn instruction was of little benefit in these two tasks, which is not a surprising result, since it did not provide relational spatial knowledge but only a live-view of the street scene (Figure 15, Table 2).

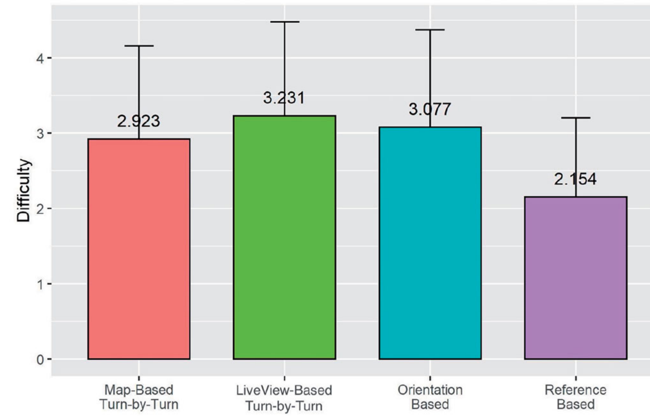


**Figure 15.** Mean and standard deviation of task difficulty scale in the unaided navigation task.

### 5.3.3. Difficulty ratings of unaided navigation

Regarding participants' perceived difficulty of the independent navigation task after receiving each of the navigation aids, we found that the perceived difficulty of REF (M = 2.1, SD = 1.0) was significantly lower than that of the other three modes (vs. MAP: M = 2.9, SD = 1.2, $t(69) = 2.2$, $p = 0.02$; vs. LIVE: M = 3.2, SD = 1.2, $t(69) = 3.2$, $p = 0.001$; vs. ORTN: M = 3.1, SD = 1.3, $t(69) = 3.0$, $p = 0.02$). There were no significant differences in perceived difficulty among the other three modes. This indicates that the participants also felt that the Reference-Based approach was the main aid that made it easier for them to independently navigate to the destination.

### 5.3.4. Performance of participants with different SBSOD scores

Finally, we examine whether participants with different levels of SBSOD scores performed differently using the four navigation aids. Our regression results of the travel time unaided navigation task showed a main effect of sense of direction on travel time ($t(24) = 2.2$, $p = 0.04$); that is, the lower the SBSOD score (the poorer the sense of direction), the longer the travel time. This result was not unexpected since research has shown an influence of sense of direction on wayfinding performance (Stites, Matzen, & Gastelum, 2020). However, what we found interesting was that the influence of sense of direction on travel time in the Reference-Based condition was considerably lower compared to that in the conditions of the other three navigation aids. We divided SBSOD scores into high and low using the median; as Figure 16 shows, participants who had a higher SBSOD score spent shorter average travel time than those who had a lower score during unaided navigation in the Map-Based (High: M = 105.1, SD = 35.3; Low: M = 121.1, SD = 60.8), Live-Based (High: M = 109.0, SD = 31.1; Low: M = 122.2, SD = 45.4), and Orientation-Based (High: M = 113.0, SD = 32.3; Low: M = 135.0, SD = 86.6) condition, respectively; however, the average travel time was similar among all participants regardless of their SBSOD score in the Reference-Based condition (High: M = 92.7, SD = 19.5; Low: M = 94.5, SD = 25.0). These results suggest an

Table 2. Means (and standard deviations) for each variable by participants in the four groups of the survey knowledge tests.

| | Map | LiveView | Orientation-Based | Reference-Based |
|---|---|---|---|---|
| Pointing Task Error(degree) | M = 20.0 (SD = 17.2) | M = 27.7 (SD = 26.4) | M = 18.1 (SD = 27.4) | M = 16.7 (SD = 17.0) |
| Map-marking Task Error(m) | M = 133.6 (SD = 167.3) | M = 163.4 (SD = 122.8) | M = 85.5 (SD = 78.1) | M = 75.0 (SD = 124.7) |

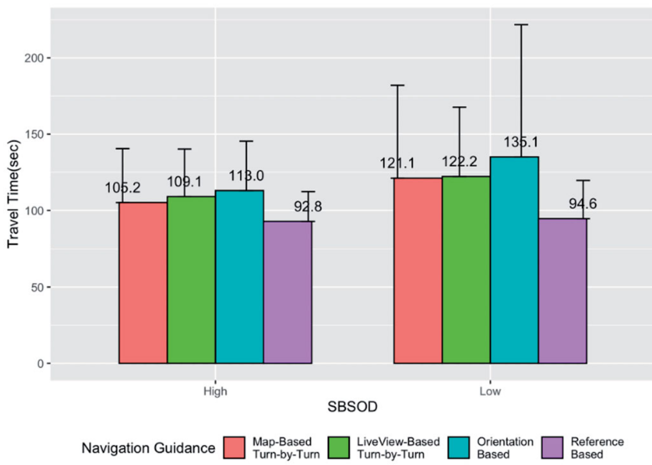


Figure 16. Participants' travel time time across high and low SBSOD scores.

additional advantage of the Reference-Based approach: it was effective in helping independent navigation even if the navigator had a relatively poor sense of direction.

## 6. Qualitative findings

Below we present our findings regarding how participants perceived the pros and cons of each navigation aid in supporting independent navigation in VR.

### 6.1. Experience with navigation aids during Aided-navigation

#### 6.1.1. Orientation-based navigation aid

Participants generally perceived it as easy to follow the orientation arrow on the top that the Orientation-Based navigation aid provides, as participants tended to carefully focus on the changes in the distance. P22 noted," *seeing the number getting smaller means that you're getting closer to the destination.*" Following only the orientation arrow made the navigation task simpler, since they perceived that they could" *just go in that direction and then eventually they would arrive,*" especially for those who perceived themselves as having a poor sense of direction. For example, it made them feel less nervous when taking a "wrong path," as long as they perceived that they were closer to the destination. Other participants noted that this also allowed them to" *incidentally learn novel routes and places they had not known before*" (P21) and" *enjoy the unexpected experience*" (P9). On the other hand, many participants thought that not providing specific route suggestions was a serious shortcoming, because they were often confused about which path to take, since" *there were many possible paths*" (P17). Some complained that they often ran into" *dead-end streets or took a longer path*" (P6) since the orientation arrow did not provide any route-related information. Furthermore, many participants pointed out that the orientation arrow caused troubles when they were nearby the destination because the drastic change in the direction that the arrow was pointing in" *was too dramatic to follow*" (P15), which would make them miss the destination if they were moving quickly.

#### 6.1.2. Reference-based navigation aid

Many participants said that the association between the reference landmark and the destination that the Reference-Based navigation aid provided made it easy to remember how to navigate to the destination because, as P15 said," *It can help me memorize the route separately because the route before the reference is already known.*" This association also made some participants feel more secure, as P5 said," *even if I was lost, at least I could make sure that I could return to the reference and figure out the next step.*" However, some participants thought transforming a text description into a spatial concept was difficult, especially for those not used to cardinal directions (P5, P19). Furthermore, participants pointed out that this approach was established on the premise that there was a known reference in the environment that the navigator already knows how to navigate to; as P8 said," *if you're in a totally unfamiliar environment, if you don't remember how to go to the reference, you can't use it.*" These drawbacks suggest room for improvement for future Reference-Based navigation aids.

#### 6.1.3. General turn-by-turn guidance

Participants thought the turn-by-turn instruction was the most efficient approach to navigating to the destination when an aid was present (P1) since they did not need to think but just had to follow the instructions (P2).In addition, the navigation aid always automatically adjusted its route based on the user's location, preventing them from worrying about getting lost especially when in unfamiliar environments. Nevertheless, participants were also concerned about their own tendency to keep staring at the phone rather than at their surroundings, which made them more likely to" *run into an accident*" (P26). In addition, the provision of a specific route made some participants think they" *would not have discovered new paths*" (P23).

Participants provided additional pros and cons for the Map-Based Turn-by-Turn and LIVE Turn-by-Turn aids, respectively. The Map-Based Turn-by-Turn aid was deemed the most familiar navigation aid for most of the participants. Additionally, those participants who preferred to plan ahead, favored this navigation aid because the map allowed them to" *drag to see the overall direction and the configuration of the environment*" (P14). A few participants deemed it troublesome and distracting when needing to repeatedly check if they had passed the destination.

Regarding the LiveView-Based Turn-by-Turn navigation aid, a few participants thought that being able to see the street scene on the interface made the navigation process easy, because it did not require them to" *project a 2D map onto the real-world environment*" (P20). It also allowed them to tell if they were on the right track because" *the interface corresponded to the street scene in the real world*" (P6). However, participants also complained that it did not allow them to" *look ahead" to know the overall configuration of the area ahead as well as the" upcoming route*" (P10) because of its first-person view and its limited range.

To sum up, during aided navigation, participants highly valued efficiency and the intelligibility of the navigation aid. Therefore, overall, more participants preferred the two turn-by-turn navigation aids for this practical reason. Nevertheless, many participants were also highly aware that using these aids made them rely on the instructions and pay less attention to their surroundings, and they expressed concerns over safety.

## 6.2. Experience in independent navigation tasks after using each navigation aid

The findings in this section provide explanations regarding why both the live view-based turn-by-turn and orientation-based navigation aids led to poor navigation performance in the unaided navigation task. The major reason was that participants either did not pay attention to their surroundings or did not attempt to remember the route they had navigated through in the aided navigation task. As a result, when in the subsequent unaided navigation task, many of them consulted their phones several times and also took more time. P2, for example, commented," *If I did not pay attention to what's next to me, I'd have no idea where I was going or where I should be going. I just had no clue.*" A few participants attributed their poor performance to the lack of street view in the Map-Based Turn-By-Turn aid. However, we found that the LiveView-Based Turn-by-Turn aid, which included such information, merely prompted just a few participants to look at the environment; the majority of the participants still paid attention mainly to their phones. For example, P12 noted," *I followed whatever it told me to do. But the bad thing was, I forgot everything too.*" Thus, while we assumed that the LiveView-Based Turn-by-Turn aid would prompt participants to pay more attention to the environment, participants tended to ignore the street live views or nearby landmarks and focus on the direction provided by the system.

Unexpectedly, a similar pattern was also found in the use of the Orientation-Based navigation aid. Although a few participants mentioned that without specific routes being provided, they could still find their own routes and thus had impressions of the things they passed by, we observed that more participants were concentrating on keeping the orientation arrow in the center front of the interface to ensure that they were moving toward to the destination. P16 noted," *I just followed the orientation, and did not actually try to remember where I turned left or right, or how many times I had make a turn. I didn't recall anything.*"

In contrast to these two modes, participants consistently thought the Reference-Based navigation aid allowed them to more easily and more quickly arrive at the destination in the independent navigation tasks because it" *forced them to think*" (P1, P24) during the aided navigation task. P12 commented," *It gave you a reference, and so you first got there and checked where you should head to. So it made you think and look around at what's around you.*" Additionally, leveraging participants' existing knowledge had made many participants think it had reduced the amount of the information they had to remember," *It's like dividing the routes into two parts. You traveled to the reference point, and then you traveled to the destination. It's like you only spent half of the time traveling, and also there was a lower mental burden*" (P20). P17 also praised the Reference-Based navigation aid," *If I used the other modes, I had to memorize a lot of stuff and routes. But if I know the reference I already knew was there [near the destination], I didn't need to remember all these routes.*"

Finally, participants who looked at the map that the Map-Based Turn-by-Turn navigation aid provided before/during the aided navigation task deemed this approach to be helpful, since they could develop an idea about" *where the destination is, how far it is, and where to take turns*" (P14, P18). Nevertheless, the majority of the participants tended to follow the turn-by-turn instructions without leveraging this advantage.

To sum up, participants were well aware of the issue regarding the lack of skill for subsequent independent navigation caused by their constant attention focused on the navigation aid rather than on the route and the environment, which was especially common while using the Liveview-Based turn-by-turn and the orientation-based navigation aids. In contrast, participants who paid attention to the environment or to the configuration of the virtual city ahead in the Map-Based turn-by-turn mode did not report such an issue. Combining these insights with the quantitative results, we consider the key factor underlying the impairment of the skill for the independent navigation task to be not the provision of turn-by-turn navigation aids per se but the navigator's tendency to rely on automated instructions.

## 6.3. Spatial knowledge acquisition

Participants also reflected on their acquisition of spatial knowledge. Regarding the pointing task, participants generally agreed that the Orientation-Based navigation aid was helpful because it directly indicated the direction at departure. Many participants thought the Reference-Based navigation aid was helpful because it helped them have a sense of in which direction the destination was relative to them. (P8). LiveView-Based Turn-by-Turn was considered helped the least helpful in this task because this mode only presented street scenes in front of the navigator, making it difficult to make sense of the overall orientation. As for

Map-Based Turn-by-Turn, some participants said the provision of a map allowed them to know the configuration of the virtual city, and thus they were able to easily point in the right direction. However, only eight participants checked the map before the navigation task.

In the map-marking task, participants were more likely to mark the location accurately if they had an accurate estimation of both distance and cardinal direction. Twelve participants reported that the Reference-Based navigation aid was the most helpful in this task because it provided a reference landmark and a verbal description that included cardinal direction and metric distance. P19 explained," *It has a clear instructions about after you see the Ferris wheel, where you should go and for how long. So you can find the reference on the map, and then you extend it to find the destination.*" The Orientation-Based aid was also deemed to be helpful because it provided metric distance and direction as instruction. Yet, a few who focused on the phone during travel deemed it was not. On the other hand, although in all navigation aids a compass was included on the interface to indicate cardinal direction, participants typically ignored the compass when using the turn-by-turn navigation aids and thus had no knowledge of cardinal direction. P18 commented on LiveView-Based Turn-by-Turn," *It doesn't helps at all on marking the map, unless you remember the street scenes very well. But this mode made you just tend to follow the arrow only. So, you wouldn't know where you were on the map.*" But again, participants who checked the map during/before navigation found the Map-Based navigation aid the most helpful because it also presented a map from a bird's-eye view perspective.

### 6.4. Influence of navigation context

Finally, many participants mentioned how the navigation context would affect their preference in navigation aids. They provided many reflections on how each of the navigation aids fits or does not fit specific navigation contexts and why they prefer one over the others in different contexts.

First of all, trip purpose was a commonly mentioned factor. Many participants mentioned that if they just wanted to travel to a place as fast as possible, they preferred a turn-by-turn approach. However, if the purpose was exploration, they preferred the Reference-Based or Orientation-Based navigation aid; as P22 said," *If the time for the trip is not restricted and I want to know the surrounding environment more, the Reference-Based Mode is more suitable for this scenario*" (P22). Associated with trip purpose is whether the navigator considers it only as a one-time trip, or possibly a trip they may repeat in the future. P26 explained," *If I'm traveling and would only visit that place once, I don't have to remember where it is. It is suitable to use the Map-Based Turn-by-Turn method. But if I'm going to a university, and I have to remember where it is and the route, I'd use the reference one, so that I can force myself to remember these.*"

Transportation mode is another factor commonly mentioned. Several participants considered that the LiveView-Based Turn-by Turn navigation aid was not suitable for driving since" *it tells when to turn only when getting close to the intersection, making it easy to miss the intersection*" (P8), and requests the navigator to" *pay attention to the arrow [in LIVE] and drive at the same time.*" (P25) As P18 commented," *You can do that while you're walking, but you can't do that when you're riding a motorcycle.*" Despite navigating in a virtual environment, the fact that vehicles were still moving on the street made participants think the vehicles were still dangerous to them and they would try to avoid them. The Map-Based Turn-by-Turn, in contrast, provided the whole route beforehand, making participants feel that they could be" *mentally prepared for making turns later*" (P8).

Familiarity with the environment is an important element that particularly impacts the suitability of using a Reference-Based navigation aid," *It is suitable for the place for which you already have some basic knowledge. Like I already know where the Ferris Wheel is in this virtual city. But if I am in a totally unfamiliar environment, I will still use the Map-Based method*" (P2). P23 expressed a desire to combine the Orientation-Based and the Map-Based Turn-by-Turn approaches:" *If you were in an environment you were unfamiliar with, first you need to know roughly the overall direction of that place, and then you'd know whether the route you're taking was right. Then the system could plan a route for you, making you feel more secure.*"

Finally, participants also mentioned that the complexity of the route and the environment mattered. It was generally considered by the participants that when the route was complex and not straightforward, orientation-based would not be suitable since they may encounter many occasions to detour and dead-end streets. For example, P8 explained," *When you have many roundabouts, this approach would be very inconvenient.*" P4 also commented," *Like I thought there's a way straight to it but it turned out to be a dead end.*" On the other hand, in environments where participants perceived that they could travel" across" rather than along the road, Orientation-based navigation was especially suitable:" *You can pass through the field, when there's no road. If I know the direction, I'd just pass through it, or like a park, any place you don't need to travel along a road.*"

## 7. Discussion

### 7.1. Turn-by-Turn instruction is not the issue. Lack of information processing is

Taking all the quantitative and qualitative findings together, we found that the key to the impairment of skills for independent navigation in VR was not the provision of turn-by-turn instructions but rather whether the participants initiated spatial information processing during navigation. Specifically, the results show that the two turn- by-turn navigation aids did not lead to poorer performance in interdependent navigation tasks and spatial knowledge acquisition. This result is somewhat different from that of Huang et al. (2012), who compared the incidental learning of spatial knowledge from mobile map-based and AR (LIVE)-based aids and found no significant differences between them, since all entailed turn-by-turn guidance and required no"

Table 3. Summary performance of each Navigation Guidance.

| | Map | LIVE | Orientation | Reference |
|---|---|---|---|---|
| Aided Navigation | Second Best | Best | Second Best | Worst |
| Unaided Navigation | Second worst | Second worst in time and distance. The worst in phone reliance | Longest distance and time. Third worst in phone reliance | Best |
| Survey Knowledge (*No significant difference in pointing-task) | Second worst (Map-marking task) | The Worst | Better than LIVE (Map-marking task) | Better than Map and LIVE (Map-marking task) |

active encoding." In our study, however, participants who leveraged the spatial information from the navigation aids performed better in the independent navigation task. That is, the participants who paid attention to nearby landmarks in the LiveView-Based aid and the participants who checked the bird's-eye view map before/during navigation both reportedly and observably performed well in the independent navigation task. Despite the two different wayfinding strategies they mainly used (the former using a route strategy vs. the latter using a survey strategy (Lawton, 1996)) in the independent navigation tasks, they both processed spatial information, which allowed them to independently navigate without consulting the phone many times. In contrast, those who mainly paid attention to the directional indicator did not encode and process spatial information during the first navigation task, causing them to have to consult the navigation aid many times during the unaided navigation task (Table 3).

This observation is further strengthened by the fact that the orientation-based navigation aid led to poor navigation performance in unaided navigation. That is, despite the fact that it offers orientation information, which is a key aspect of survey knowledge, the presence of the orientation arrow made many participants tend to focus on" tuning" the arrow, neither paying attention to the environment nor processing the orientation information that was supplied. In contrast, those who treated the orientation arrow only as a reference and explored their own routes did not have this issue. This made us conclude that the key to the impairment is not the automated updates of turn-by- turn instructions per se but instead whether users process spatial information on their own. These results tend to suggest that although modern turn-by-turn navigation aids tended to provide additional information to strengthen users' spatial knowledge, whether the information is utilized largely depends on the users. As many participants also reflected, the reason why the Reference-Based navigation aid could enable them to navigate smoothly and efficiently in the unaided navigation task, even as efficiently as following a turn-by-turn instructions, was that they were" forced to process the given spatial information at hand" when they received the aid. Consequently, we argue that regardless of the amount of survey knowledge information provided, the key was acknowledging users' propensity to follow automated instructions and thinking about how to prompt or encourage them to process the spatial information despite such propensity during navigation.

That being said, we note that there are several differences between navigating in the physical world and navigating in VR. For example, navigation in VR is virtual, meaning that it does not involve physical movement and that collisions in VR does not cause actual harm to the navigator's body. The temporary and physical effort involved in navigating in VR is also typically lower than that in the physical world. For example, we expect that heading into the wrong way using an orientation-based approach can be quite frustrating in the physical world, and this may make navigators be more careful when following the orientation guidance. Thus, we speculated that if the experiment had been conducted in the real-world, the participants might have paid less attention to their phones and more attention to the environment, respectively, than they would in VR, due to the greater concerns about safety and travel costs. Furthermore, a reliable navigation aid can be assumed to be permanently available in VR, but positioning technology will not necessarily be available in the physical world. Thus, navigators in VR may have less incentive to acquire spatial knowledge than those in the physical world. Taking these factors into account, it is likely that navigators in VR have a higher tendency to rely on navigation aids in VR than they do in the physical world. That is, the over-reliance on navigation aids in VR might be more serious than it is in the physical world. If this is true, it is likely that navigators in the real-world may have a lower tendency of simply following orientation arrows and will acquire better orientation knowledge. Given that the current study is focused on virtual worlds, future research will be needed to verify this assumption.

### 7.2. Selecting a navigation aid based on the navigation context

Our results also suggest that there is no single best navigation aid in VR, at least for now. Which one is better depends on the suitability of the navigation aid for the navigation context, the latter of which includes the purpose of the trip and the characteristics of the trip and the environment. Not only did we quantitatively show the different levels of performance achieved by different navigation aids, but qualitatively we also showed that many participants displayed different preferences in different navigation scenarios. We suggest that future navigation systems provide (and combine, if necessary) different kinds of navigation aid based on the navigation context. Based on the results, in the following we suggest five contextual factors that future navigation systems can consider.

#### 7.2.1. Trip purpose: efficiency vs. exploration

The navigation system should consider the purpose of the trip–whether it is efficiency-oriented or exploration-oriented.

If it is efficiency-oriented, turn-by-turn instructions would allow users to most efficiently arrive at their destinations. It is particularly suited to trips that are considered time-sensitive. When the users have a more relaxed schedule and have an intention to explore the environment or discovering new routes, providing global orientation and reference point information can help them explore their own paths with different benefits. While the former makes users aware that they are getting closer to or farther from a target, the latter provides an anchor point that can make users feel secure when exploring. If the user intends to expand their vicinity from the places they already know, associating the target with a known reference point is particularly suitable for them to easily expand their cognitive map. Currently, we have not seen a mobile navigation aid that has leveraged this feature in its navigation system, but we believe it would provide great benefit in helping them learn about the environment and think this approach should be easily implementable in VR.

#### *7.2.2. Transportation mode*

Our results also indicate that the navigation system should consider whether the navigator is undertaking pedestrian navigation or vehicle navigation if the virtual environment is to simulate how people travel through the physical environment in how people travel through it. Liveview-based navigation is more suitable for pedestrian navigation as it requires more of the user's attention and can cause danger in vehicle navigation. Supplying global orientation and configuration information (e.g., map) is beneficial when the users are far from the target, but it can cause problems when users are close to the destination, especially when in a vehicle, where higher speed is likely to cause the change in direction to be too dramatic too follow and thus can potentially lead to danger. We suggest that the system supply global orientation information when the destination is still distant and only provide turn-by-turn instructions when close to the destination.

#### *7.2.3. Familiarity with the environment*

When users have basic familiarity with the surrounding environment, such as navigating in the area where they reside or frequently stay, it is easier to fulfill the prerequisite of using a reference-based navigation aid. If users are familiar with the environment, they may know more places in the area that allow the system to associate the destination with. However, the system may not find close or sufficiently salient known places that users know in the environment the users are unfamiliar with. Most participants reportedly preferred using a navigation aid that provides a specific path when traveling in an unfamiliar environment because it made them feel more secure.

#### *7.2.4. Potential of revisiting*

If users perceive that they will revisit the destination or the area around it in the future, they have more motivation to learn about the routes. The system can prompt users and ask their purpose for the trip as well as whether they anticipate revisiting the place in the future. If users hope to learn about the routes to the destination for future use, the navigation system, if using turn-by-turn instruction, should consider whether the users prefer a survey strategy (e.g., map) or route strategy (street scene) for wayfinding and enhance their route knowledge or survey knowledge accordingly. The preference can be either explicitly inquired via questions or inferred from their level of map usage during navigation. This is based on the assumption that if they are motivated to learn, they would also be motivated to process the supplied additional spatial information rather than only focusing on following the instructions. On the other hand, if the system detects that a reference point that users may know is nearby the destination, it can supply additional information to the user regarding where the destination is related to the reference point. As shown earlier, this association is the most advantageous in helping users learn about how to independently navigate, and it is easy to process. Additionally, to help users better process spatial information better, the system can consider including spatial knowledge quizzes, such as in Parush et al. (2007) and Wen et al. (2014).

#### *7.2.5. Environment complexity*

Finally, if the virtual world includes areas that have a relatively complex or irregular road network, such as containing roundabouts, detours, and dead-end streets, global orientation is clearly insufficient in these areas. We suggest that the navigation system in VR provide a clear and specific route to indicate the planned path. Alternatively, we suggest supplying global orientation information in environments with a simple structure, especially those where users can travel across, for example, fields instead of traveling along the road.

## 8. Limitations

The current research is subject to several limitations. First of all, in our Reference-Based navigation aid, we adopted verbal description and cardinal direction to describe where the destination was in relation to the reference point. However, this might not be the best way to present the relational information of the reference. Future work can consider better ways to present such relational information, such as using visualization techniques. Second, the present study also compared the performance among the four navigation aids only for pedestrian navigation without considering different modes of transportation, such as driving or riding scooters. Future research can compare the performance using different modes of transportation. Also, we encourage future research to assess novel navigation aids–not only how well they help the navigation process when the aid is present but also whether and how well the navigation aid helps the navigator acquire knowledge of the environment and enables them to navigate without the aid.

Third, we did not consider different navigation scenarios but assumed that efficiently arriving at the destination was the primary task. Yet, we have learned that navigation context matters. Therefore, we think that future studies can revisit this research topic in different navigation contexts. Fourth, participants were likely to have acquired knowledge of the virtual city before the study from the video demonstration we provided. This might have made the navigation to the destination that was relatively close to the reference point easier for the participants. Fifth, although we counterbalanced the order of the four navigation aids and included the order effect in the regression model to account for its variance, the within-subjects study design might have more consequences that influenced the study results that could not be fully explained by including the order effect. For example, participants in subsequent rounds might have higher spatial awareness, which would change their level of attention to the environment. Sixth, the sample size in the study was relatively small. It is likely that some statistically non-significant results were due to the small sample size. Furthermore, some differences among the navigation aids might have been more statistically significant if we had recruited more participants. We encourage future research to examine the results with a larger number of participants.

## 9. Conclusion

In this study, we visit the issue of skill impairment for independent navigation tasks in virtual environments, which is an issue that has been argued to be a downside of turn-by-turn navigation aids. We compared two modern turn-by-turn navigation aids with two non-turn-by-turn navigation aids that we designed for supplying spatial information. We show that the key to the impairment is users' tendency to rely on automated instructions instead of the provision of turn-by-turn navigation aids per se. This conclusion was established first by the observation of participants who leveraged the spatial information provided by the two turn-by-turn navigation aids in their aided navigation task and performed well in the independent navigation task. And, it is further strengthened by the unexpected result that the provision of global orientation information led to poor navigation performance in independent navigation tasks because many participants mainly paid attention to their phones rather than to their surroundings and the spatial information the system supplied. Thus, providing spatial information during navigation in VR does not guarantee subsequent successful independent navigation. By the same token, supplying an automated turn-by-turn navigation aid in VR is also not an issue as long as the design of the system can prompt users to process spatial information. On the other hand, we also show that there was no best navigation aid in VR from the users' point of view. Instead, they preferred specific kinds of navigation aids depending on the purpose of the trip and the characteristics of the trip and the environment. We thus suggest that future navigation aids in VR focus on two directions–providing navigation aids depending on the navigation context and designing a mechanism that makes users more likely to process spatial information during navigation–if the system also expects the users to be able to independently and freely navigate in the virtual environment without reliance on navigation aids.

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