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Enhancing human indoor cognitive map development and wayfinding performance with immersive augmented reality-based navigation systems

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ABSTRACT

Augmented reality (AR) is an interactive experience where computer-generated perceptual information is superimposed into the real-world environment. Most existing research in AR-based wayfinding has focused on the technological aspects of developing AR-based software or devices to realize navigation. No previous investigations have focused on understanding the impact of immersive augmented reality (IAR)–based systems on human wayfinding performance from the cognitive perspective. Aimed at investigating the influence of IAR-based systems on people's cognitive map development and their subsequent wayfinding performance as well as the effect of using three-dimensional (3D) layout models in IAR environments in addition to superimposed guideposts, an experiment was carried out in a building with a complex floor plan. A total of 54 university students were evenly divided into three groups: a control group with no IAR assistance, a second group using an IAR-based navigation system that includes only superimposed guideposts, and a third group using an IAR-based navigation system that includes both guideposts and a 3D layout model. Each participant was asked to conduct a spatial exploration task in the environment, sketch a floor map based on their spatial cognition, and perform a wayfinding task to find eight specific locations in the building. An analysis of the participants' performance and responses to a number of self-evaluation questionnaires collected in the experiment indicates that IAR technology can help people develop their cognitive maps more effectively and can substantially improve their wayfinding performance with a much lower workload. A second finding is that adding a 3D layout model can enhance the effect of an IAR-based navigation system in terms of cognitive map development. The findings from this research extend the existing knowledge about IAR-based navigation and further verify that AR technology has the potential to reduce human workload for cognitive tasks. The results also could support its more effective application in various scenarios that require assisted wayfinding and cognitive map training, such as emergency evacuation drills.

1. Introduction

Indoor wayfinding is a process in which people try to orient themselves and navigate in an indoor environment with the objective of finding their way from an origin to a destination [1]. It involves knowing the current location and destination, finding the best route to the destination, recognizing the destination upon arrival, and finding the way back, if needed [2]. Wayfinding in complicated buildings such as airports or hospitals is a stressful and sometimes challenging task because the entire environment cannot be perceived from a single vantage point [3]. The loss of opportunity and time due to disorientation has been well researched and documented [4]. Wayfinding studies are particularly important for the emergency evacuation of buildings (for example, in the case of a fire or an earthquake), where efficient wayfinding is critical for saving lives.

Vilar et al. [5] differentiated studies in the field of wayfinding into two categories, focusing on either external information (environmental factors) or internal information (cognitive representation). Environmental factors covered in existing research studies include landmarks [6], differentiation [7] and layout complexity [8], among many others. For internal information, individual characteristics were investigated such as age [9], cultural influence [10], level of disability [11], and

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cognitive maps [12]. Among these factors, the cognitive map is one of the most important: cognitive mapping is the first cognitive process of and a basis for wayfinding [13–15]. Wayfinding refers to the process where a person acquires and encodes environmental cues as spatial cognition in a cognitive map and then makes a route plan and executes the route plan with the knowledge acquired from cognitive mapping to complete the wayfinding task. The cognitive map, a term first introduced by Tolman [16], can be later retrieved to improve wayfinding performance. The cognitive map is a mental representation of the spatial relationships between the essential points, places, objects, and other features in the environment and the possible connections between them [17]; wayfinding tasks highly rely on the cognitive map, and people may become lost in situations where their cognitive maps are inaccurate, incomplete, or distorted [18].

Navigation technology is often used to facilitate human wayfinding behavior [19] and help people to develop an internal cognitive map [20]. It is important to investigate the effect of navigation technology on the user's wayfinding performance and the development of a cognitive map for two reasons. First, in the real world, people need navigation systems to reach their destinations quickly and accurately. In addition, for some people who need to develop cognitive maps, such as pilots and drivers, helping them to establish a cognitive map as quickly as possible to reduce their dependence on the navigation system as well as to reduce their mental load is also very important for navigation technology. In the field of emergency rescue, firefighters use a cognitive map strategy during search and rescue to remember the escape route in a building [21]. Second, many previous studies have indicated that navigation modes would influence the development of human cognitive maps and human wayfinding performance. By reviewing the literature on different navigation modes, it can be seen that when compared to navigation with no aids, traditional mobile navigation in a real-world environment (including mobile navigation based on the Global Positioning System (GPS)) and mobile navigation in a virtual reality environment can improve the efficiency of human wayfinding [22,23]. However, several studies indicated that mobile navigation could be detrimental to the development of cognitive maps, and one of the main reasons for this is the potential for mobile navigation to distract the user from attending to the surrounding environment [24,25]. In addition, visual-based mobile navigation is also classified into two types: guidepost navigation and navigation using "you are here" (YAH) maps that indicate the user's current location. Previous research has generally found that guidepost navigation is more efficient than a YAH map [26]. In addition, it is generally accepted that three-dimensional (3D) maps are more beneficial in establishing a cognitive map than two-dimensional (2D) maps [27], whereas 2D maps have a more positive effect on human wayfinding performance than 3D maps [28,29]. However, some emerging navigation technologies have not been adequately studied.

Among the emerging technologies employed to develop navigation systems in recent years, a prominent example is augmented reality (AR) technology. AR is a novel technology that can enhance human contextual perception by adding super-imposed computer graphics and overlaying information to the user's view of the real world [30]. It has been used for various applications related to the built environment, including architectural design, facility management, and indoor navigation. AR-based tools used in wayfinding studies began with hand-held devices and then progressed to head-mounted AR (HMAR) devices. As the latest immersive augmented reality (IAR) technology, HMAR can overlay digital information onto the users' view [31] and help them see the environment clearly while they follow the navigational information cues provided by AR. Thus, when using IAR navigation systems, people will not need to transfer their attention away from the environment to the navigation information provided in the overlay [32]. This characteristic of AR has helped people to improve the quality of tasks that they perform [33] and to reduce their mental load [34]. Hence, IAR navigation systems may not impede the establishment of a cognitive map as would a traditional mobile navigation system. In addition, a recent study of hemodynamic measures indicated that a wearable display provided by a well-designed HMAR device produced the lowest mental workload and improved situational awareness in both navigation and visual perception tasks [35]. With these advantages—which are significantly different from those of traditional navigational aids such as GPS units, mobile phones, and other devices—AR has the potential to improve the performance of human wayfinding as well as to facilitate the formation of cognitive maps, making it more likely that this navigation system will be widely used in the future.

Two different navigation modes in AR technology can facilitate the human navigation process: in one mode, a virtual guidepost is projected onto the users' view so that users can passively follow the directional arrow to the desired destination [36–40]; the other mode, which is less common but is a more creative approach, is to overlay a 3D layout model (a 3D representation of the floor plan) onto a view of the real world [41,42]. Most existing AR-related navigation tools employ the first mode to achieve a particular wayfinding purpose, e.g., a system for senior citizens to guide them when they become lost or disoriented [43], a guidance system for tourists [44], or a navigation aid for the intellectually disabled [45]. Previous studies have explored the functionality of IAR-based navigation systems and focused on user experiences of IAR-based navigation systems including, for example, user preferences regarding different AR tracking techniques [46] and user behavior when interacting with IAR-based navigation systems [47]. However, the way that guidepost-based IAR-based navigation systems influence human wayfinding performance and how they help in establishing human cognitive maps has not been explored. In addition, few studies focus on applications that include a 3D layout model in an IAR-based navigation system, and even fewer investigate the effectiveness of a novel 3D layout model function in improving human wayfinding performance or on establishing a human cognitive map.

Compared to the extensive research that has already been published on traditional mobile navigation, mobile navigation that is based on IAR has yet to be widely investigated, and little research focuses on evaluating the effectiveness of the two available AR modes. Motivated by such gaps, in the research reported here, a HoloLens-based IAR indoor navigation system was developed that incorporates both types of modes (a mode that shows guideposts and a mode that uses projection of a holographic 3D layout model in addition to guideposts), and the effects of this system under both modes on human wayfinding performance and cognition maps were examined. When wearing a HMAR display, people can look through the lens and see the surrounding physical environment, onto which virtual spatial information has been superimposed. The following two research objectives are investigated in this study: (1) To explore the effect of an IAR-based navigation system with guideposts on human wayfinding performance and the development of a cognitive map, and (2) To study the effect of 3D layout models in an IAR environment on human wayfinding performance and the development of a cognitive map. To address these two questions, IAR-based wayfinding behavior experiments were conducted, and the results are reported and discussed in the sections that follow.

2. Methods

2.1. Overview

To realize the two objectives in this paper, wayfinding behavioral experiments based on IAR navigation systems were carried out. Only one independent variable was set in this study, which is the mode of the navigation system. Participants in the study were divided into three groups (Group A, Group B, and the Control Group). Groups A and B were used to test the effect of two different IAR-based navigation systems on wayfinding performance and on the development of cognitive maps: participants in Group A used a system with virtual guideposts only, while those in Group B used a system that included both virtual guideposts and 3D layout models. Participants in the Control Group were asked to complete the wayfinding task without using any AR navigational aids. The Control Group was set to be the base of comparison to eliminate the influence of possible confounding variables on the results and to enhance the reliability of the results. Groups A and B used different navigation modes, and the results for these two groups were compared with those of the Control Group to explore the effects of different navigation modes on wayfinding performance and on the development of cognitive maps. To control for confounding variables, the demographic information (age and gender) [9] of the study participants as well as the participants' scores on the Santa Barbara Sense of Direction (SBSOD) questionnaire [48] were collected and analyzed, because these variables are known to influence wayfinding performance.

Qualitative and quantitative data were considered as dependent variables to measure the participants' wayfinding performance and the development of cognitive maps. The wayfinding in this paper requires the participants to orient themselves and navigate in the selected building with the objective of finding their way from an origin to the destination without the navigation assist. The cognitive map is the spatial cognition as which people acquire and encode environmental cues during the exploration with the navigation system assist. Wayfinding performance of the participants was quantified by measuring their wayfinding time, extra path length, number of incorrect decisions, and number of pauses in wayfinding process. The participants' cognitive map was measured by the sketch map score [49]. With respect to the measurement of participants' mental load, both subjective and physiological methods have been developed in the literature [50]. This study, like a number of prior studies [51,52], used the subjective method only. Specifically, to measure participants' workload including mental load associated with wayfinding and the development of cognitive maps, the National Aeronautics and Space Administration task load index (NASA TLX), a classic workload-measuring scale, was used at multiple steps of the experiment. In addition, self-evaluation of the difficulty of the wayfinding and the development of a cognitive map was also reported by the participants. Finally, in order to determine the application prospect of the IAR-based navigation systems, questions about the usability of the HoloLens were also be measured by the way of self-report. All variables are summarized in Table 1.

Table 1
Summary of the Variables.

Type of Variable	Variable	Objective of Measuring the Variable
Independent variable	Modes of the navigation system	To explore the effects of different navigation modes on wayfinding performance and the development of the cognitive map.
Concomitant variable	Age	To collect age information and to examine whether participants' ages influence the participants' performance.
	Gender	To collect gender information and to examine whether the participants' gender influences the participants' performance.
	SBSOD	To measure participants' sense of direction and to examine whether the participants' sense of direction influences the participants' performance.
Dependent variable	NASA TLX score	To measure the participants' workload for wayfinding and the development of cognitive map.
	Sketch map score	To measure the participants' cognitive map.
	Wayfinding time	To measure the participants' wayfinding performance.
	Extra path length	To measure the participants' wayfinding performance.
	Number of incorrect decisions	To measure the participants' wayfinding performance.
	Number of pauses	To measure the participants' wayfinding performance.
	Self-evaluation questions for difficulty	To measure the difficulty of performing the experiment.
	Questions about the usability of the HoloLens	To measure the usability of the IAR-based navigation systems.

Fig. 1. Microsoft HoloLens.

2.2. Participants

The 54 participants recruited in this study were all students at Tianjin University who had not previously visited the building selected for this study. All participants were organized into three groups: Group A, Group B, and the Control Group. Each group contained 18 participants and had the same ratio of males to females (2:1). The mean and standard deviation of the participants' ages in each group were 21.00 ± 1.69 years for Group A, 22.33 ± 2.01 years for Group B, and 22.29 ± 1.93 years for the Control Group. All participants were in good physical condition and had normal visual acuity (either with or without correction). Successful participants received a small monetary reward of 25 RMB (approx. 4 USD) after completion of the experiment. There were no significant differences in the participant groups in terms of their sense of direction, age, or gender ratio.

2.3. Apparatus

A Microsoft HoloLens [53], as shown in Fig. 1, was used in this research to support an IAR environment. With a built-in Windows operating system, the HoloLens is a flexible and extensible solution for many IAR-based applications and is available to the general public. Several key features make the HoloLens a cutting-edge HMAR device. Spatial mapping provides a detailed representation of real-world surfaces in the environment and makes it possible to place virtual objects on real surfaces [39]. At the same time, the HoloLens employs an inside-out tracking system that uses two low-resolution cameras to observe features in the environment, and it fuses this information with data from an inertial measurement unit (IMU) to determine the precise position of the HoloLens [39]. After observing the environment and identifying the current location as an important point in the world that the system must track over time, the system uses a spatial anchor to ensure that holograms (the data augmented into the real world) stay precisely in place.

There are three steps involved in the development of this IAR-based environment: 3D modelling, coding, and deploying. Based on the detailed computer-aided design (CAD) plan drawings of the floor of the selected building, the indoor environment was first modeled in *Autodesk 3DS Max* [54] in order to include all information to be augmented into the real world, such as directional arrows and name annotations for all the guideposts. Next, models in Filmbox format were imported into the *Unity 3D* interactive experience development platform to enable functional programing. The Vufoira Software Development Kit (SDK) [55] was used to develop the AR overlay and the spatial anchors to register the guideposts and the 3D layout model to the correct position in the real world. Lastly, the IAR-based environment was packaged into Android application package (APK) format to enable deployment in the HoloLens through *Microsoft Visual Studio*.

2.4. Experimental environment

The third floor of a campus building at Tianjin University (Tianjin, China) was used as the indoor environment for this experiment. The entire floor had an area of approximately 9,000 m^2, out of which the experimental area covered approximately 6,000 m^2. As shown in Fig. 2, the layout of the experimental area featured a total of 54 rooms, 8 intersections, and 14 corridors. Among all the rooms, 8 rooms were selected as destinations for the exploration task and wayfinding task. The above spatial layout is relatively complex compared to previous research that addressed similar research topics [26,56]. The eight selected rooms were labelled using the following names: Classroom, Meeting Room, Lab, Activity Room, Discussion Room, Tea Room, Lounge, and Office. Six intersections were chosen as decision points, which are the places where the participants need to make choices regarding which way to turn. Waypoint signs were already posted on the wall before the experiment. However, the selected rooms of the building in the experiment were renamed and the new names of the selected rooms were different from the names listed on the existing waypoint signs on the wall. The participants were asked to ignore the posted signs and were told to rely on the IAR-based navigation systems and the new names marked on the selected rooms.

A quick response code (QR code) was placed on the wall next to each decision point (the locations are indicated by the blue dots in Fig. 2). These QR codes act as spatial anchors, and they are required by the HoloLens to precisely place the holograms in the environment. For an environment with any dimension larger than five meters, the HoloLens may be not stable in associating its own position with the spatial map developed for the environment. Fortunately, this problem can be solved by placing a spatial anchor to calibrate the coordination systems for the holograms and the environment. Participants can scan the QR codes using the HoloLens to update and calibrate the navigation information.

Two key types of navigation information were provided in the developed navigation system. First, a virtual guidepost was superimposed onto the physical view at decision points, as shown in Fig. 3, to achieve real-world navigation. In the second type, users called up a 3D layout model showing a single floor stereogram that indicated the users' current position and the locations for all other key rooms at decision points, as shown in Fig. 4. When the participants were at a decision point and scanned the QR code, the guidepost and the 3D layout model would emerge simultaneously. The virtual guidepost and 3D layout were overlaid onto the image of the indoor environment simultaneously, as shown in Fig. 5. The guidepost points to the destination where the road in front of the participants would lead. Although the 3D layout shows a single floor, the model is a three-dimensional spatial model and includes a feature that allows users to rotate and zoom in and out. The 3D layout also shows the participant's current location.

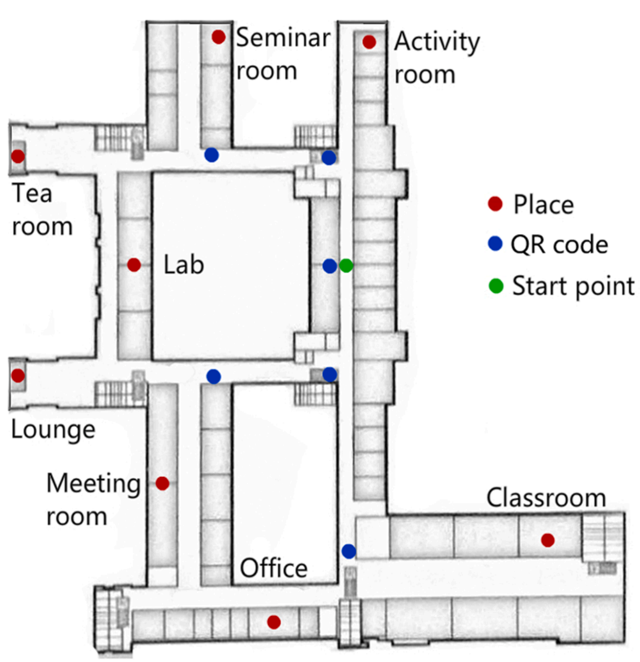


Fig. 2. Layout of the indoor environment.

Fig. 3. Guidepost at a decision point.

2.5. Experimental procedure

The test procedure comprises six steps, which are detailed as follows:

Step 1: Pre-experiment questionnaire survey. A survey questionnaire was given to each participant in order to collect demographic information (such as name, age, and gender). Participants were also asked to complete the SBSOD questionnaire [48], which was used in this study to control the variable of sense of direction. Informed consent forms were also obtained from each participant.

Step 2: IAR training. After completing a pre-experiment questionnaire, the participants were randomly assigned to Group A, Group B, or the Control Group. Participants in Groups A and B completed a brief training session on the use of the HoloLens and the IAR-based navigation system prior to the experiment so as to familiarize them with the environment of the IAR and the operation of the HoloLens. In this training session, participants were permitted to wear the HMAR device and could ask the experimenter for help if they had any navigation problems. The purpose of the training was to ensure that all participants would be ready to use the IAR-based navigation system and would not underperform in the subsequent wayfinding tasks due to their unfamiliarity

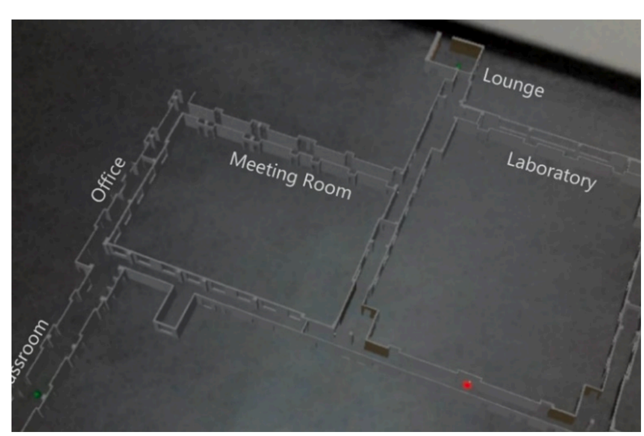


Fig. 4. 3D layout model.

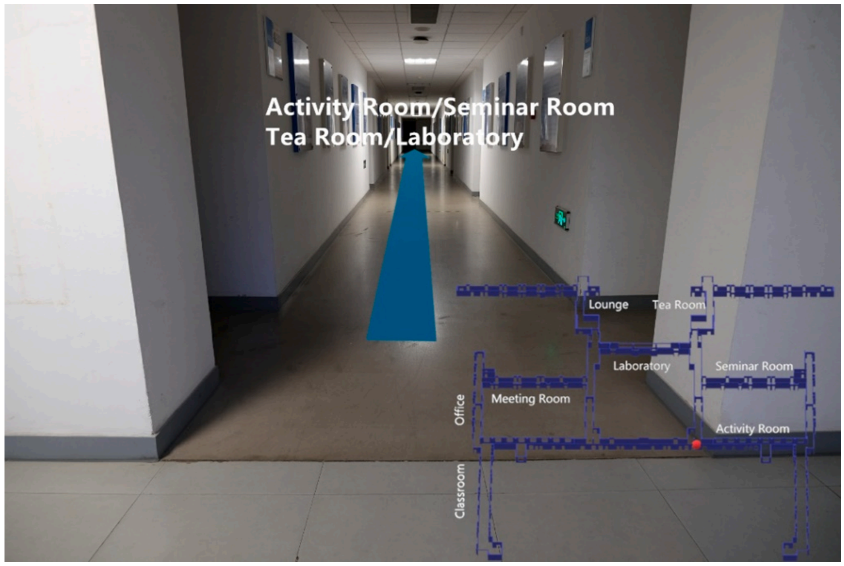


Fig. 5. Guidepost and 3D layout model at a decision point.

with the equipment.

Step 3: Exploration task. In the exploration task, each participant was asked to find all eight rooms (indicated by red dots in Fig. 2), beginning at the start point (the green dot in Fig. 2) and exploring freely. Participants were asked to explore freely for up to 15 min. All participants were asked to remember the locations of all eight rooms and the layout of the environment. They could stop the exploration when they felt that they were familiar with the layout. This experimental design is used commonly in prior research on cognitive map [29] and wayfinding [57]. All participants successfully completed the exploration task within the time limit. Participants in Groups A and Groups B wore a HoloLens equipped with different IAR-based navigation systems during this task, while participants in the Control Group did not use any navigation aid while exploring. Participants in Group A and Group B were able to scan the QR code with their HoloLens at decision points to call up the navigation system, as shown in Fig. 6. The NASA TLX questionnaire [58], which uses a 20-point Likert scale, was administered after the exploration task and was used to assess the participants' multidimensional workloads, including their mental workload, physical workload, time pressure, task performance, effort, and frustration when completing this task.

Fig. 6. QR code used as a spatial anchor.

Step 4: Sketch map task. Sketching is a common way to make a cognitive map explicit and to measure its development [59]. All participants were asked to sketch a map showing the layout of the test environment immediately after the exploration task to investigate the development of their cognitive maps in order to assess the impact of the IAR-based navigation system on the cognitive maps in their brains. An example of a sketched map that would be produced in this task is shown in Fig. 7.

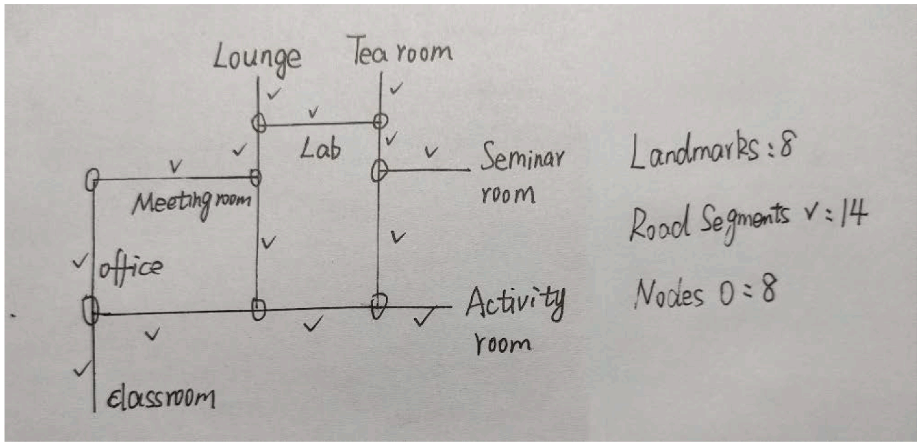
Step 5: Wayfinding task. This task was designed to test the establishment effect of human cognitive maps. At the initial start point (the green dot in Fig. 2), all participants were asked to perform a wayfinding task immediately after they finished the map sketching to find five specific rooms (Classroom, Meeting Room, Rest Room, Seminar Room, and Laboratory) in a given sequence without using any additional aids including the navigation system and the sketch map. After performing this wayfinding task, the participants were once again asked to complete a NASA TLX questionnaire.

Step 6: Post-experiment questionnaire survey. A post-experiment survey was conducted to collect all participants' self-evaluation of their task performance and their opinions on the usability of the IAR-based navigation system. The questionnaire included eight questions (Table 2) designed to understand the experiment difficulty and psychological anxiety through self-evaluation along with seven questions (Table 3) regarding the usability of HoloLens (including its efficiency, its effectiveness, and their satisfaction with the use of the device) [60]. All questions on this survey were scored on a five-point Likert scale.

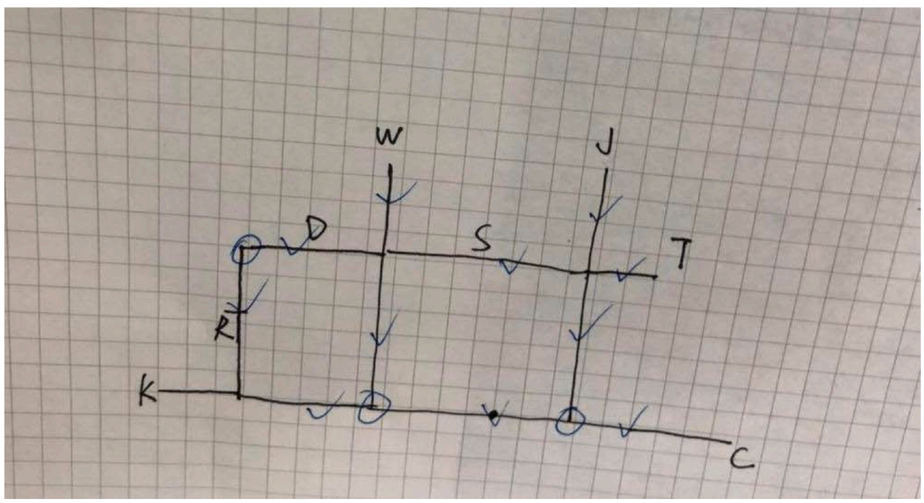
2.6. Data collection

The data collected in Step 1 included demographic information (name, age, and gender) about the participants as well as their scores on the SBSOD questionnaire. The SBSOD questionnaire is a self-reported measure of environmental spatial ability that evaluates people's sense of direction by summing up their reported level of agreement on a set of statements related to their spatial and navigational abilities and their preferences in everyday life experiences.

Data collected in Step 3 included the scores for participants' workloads that were obtained using the NASA TLX Workload Scale and the exploration time. In the weight of different factors in the NASA TLX Workload Scale, there are 15 possible pairwise comparisons of the six scales. Each pair was presented to the participants on a card. Participants circled the member in each pair that indicated which option they felt contributed more to the workload of that task. The number of times



(a) An example of a sketched map with full marks of 30 points.



(b) An example of a participant's sketched map with marks of 14 points.

Fig. 7. Examples of sketched map evaluation.

Table 2
Self-evaluation Questions.

#	Question
1	To what extent did you feel anxious when looking for the eight locations in Step 3 of the experiment?
2	To what extent did you remember all eight locations after Step 3 of the experiment?
3	To what extent were you familiar with the floor layout after Step 3 of the experiment?
4	Overall, how difficult did you think Step 3 of the experiment was?
5	Overall, how difficult did you think Step 4 of the experiment was?
6	How confident were you in completing Step 5?
7	To what extent did you feel anxious during the wayfinding task (Step 5 of the experiment)?
8	Overall, how difficult did you think Step 5 of the experiment was?

Table 3
Questions about the Usability of the HoloLens.

Type	#	Question
Efficiency	1	How easy do you think the AR helmet navigation system is to use?
	2	How well do you know how to use the AR-based navigation system in this experiment?
Effectiveness	3	How useful do you think the AR-based navigation system is for indoor navigation in complex buildings?
	4	How useful do you think the HMAR system is when helping you become familiar with and remember the interior layout of the building?
Satisfaction	5	How interesting do you find the AR-based navigation system?
	6	How much would you like to use the AR-based navigation system again?
	7	How strongly would you recommend the AR-based navigation system to your friends?

that each factor was selected was tallied. The total number of tallies could range from a minimum of zero to a maximum of five. Then the scores for all six factors and the weighted average of the NASA TLX could be calculated. The exploration time was recorded and collected by the experimenter.

In Step 4, a sketch map was obtained from each participant. Following recommendations in prior research [49], the evaluation of each sketch was based on the number of correct landmarks, the number of correct road segments, and the number of correct nodes. Scores for those three aspects were summed to obtain a total sketch map score. For instance, Fig. 7a shows a standard answer with full marks of 30 points, and Fig. 7b shows a participant's sketch map with marks of 14 points, which included zero correct landmarks, 11 correct road segments, and three correct nodes. This method was adopted in this study because it is believed to be a valid method for representing a person's cognitive map and evaluating it, as many existing studies have reported using the sketch map method to quantitatively evaluate an individual's familiarity with an environment [61–63].

The following data were collected in Step 5 as indicators of wayfinding performance:

- Total time. This measure is the total time it took for the participant to find all five rooms.
- Extra path length. The extra path length indicates the difference between the length of the participant's actual path and the length of the minimum (or optimal) path for a given task. The actual path for each participant was depicted on a floor plan drawing by an experimenter, who followed the participants during the experiment. The path length for each participant was then measured based on the plan drawings of the building, and the total path length was calculated. This study used the incorrect path ratio, which is the ratio of the incorrect path length to the minimum path length; this ratio has been used in many published studies to measure an individual's performance in a wayfinding task [61,64–66].
- Number of incorrect decisions. An incorrect decision was counted each time a participant turned in a direction that did not point to the optimal path at a decision point (an intersection point) [66].
- Number of pauses. A pause was counted each time a participant stopped and stood still for more than two seconds during the wayfinding task [5].

All data obtained in Step 5 was recorded and collected during the wayfinding task by the experimenter, who closely followed the participants while taking care to ensure that participants would not be interrupted.

Finally, data collected in a post-experiment questionnaire conducted in Step 6 was collected and analyzed to aid in understanding the difficulty of this experiment and the usability of the HoloLens. This questionnaire used five-point Likert metrics.

2.7. Data analysis

For data that were found to not meet the statistical assumption of a parameter test (normal distribution and homogeneity of variance)—including data such as free exploration time, sketch score, wayfinding time, incorrect path length (ratio), incorrect decisions, pauses in wayfinding process, and some of the metrics data (e.g., self-evaluation of task performance and usability evaluation results)—a Mann–Whitney U test was conducted to analyze the differences between groups. For data that were found to meet the statistical assumption of a parameter test (including the NASA TLX), an analysis of variance (ANOVA) single factor analysis was conducted. The least significant difference (LSD) test method was included for post hoc multiple comparisons between two the experimental groups and the control group separately after the ANOVA.

3. Results

3.1. Participants' overall performance in exploration and wayfinding

The overall results in exploration and wayfinding for all three groups are shown in Table 4. No significant difference was found in environmental spatial ability among the participants in the three groups. It was noted that on average, the participants in Group A and Group B showed better performance than those in the Control Group: they had higher scores in the sketching map task, had shorter wayfinding time, and made fewer mistakes. To determine whether the differences between groups are significant or not, a Mann–Whitney U test was used to analyze the data. In Tables 5 and 6, the performance of the Control Group is compared to that for Group A and Group B, respectively. In this test, the significance level was set at 0.05 and the marginal significance level was set as 0.10.

In terms of free exploration time in Step 3, the average time for participants in Group A and Group B were very similar, with times of 603.28 sec and 599.72 sec, respectively. Both times were longer than that for participants in the Control Group (532.72 sec). A non-parametric test showed significant differences between the Control Group and Groups A ($p = 0.022 < 0.05$) and B ($p = 0.044 < 0.05$).

The results for the sketch map score showed that the average scores of participants in Group A and Group B were relatively comparable, with scores of 20.83 and 21.33, respectively; these scores were both higher

Table 4
Overall Performance of Participants in All Groups.

Step	Indicator	Group A Mean (SD)	Group B Mean (SD)	Control Group Mean (SD)
Step 1	SBSOD score	62.06 (17.13)	59.78 (17.63)	62.28 (13.97)
Step 3	Exploration time (sec)	603.28 (91.8)	599.72 (88.24)	532.72 (79.84)
Step 4	Sketch score	20.83 (5.51)	21.33 (4.65)	16.78 (5.39)
Step 5	Wayfinding time (sec)	351.33 (102.62)	313.11 (42.91)	398.94 (141.72)
	Incorrect path length (m)	102.38 (132.22)	47.89 (55.88)	159.73 (164.2)
	Incorrect path ratio	0.17 (0.17)	0.10 (0.11)	0.24 (0.19)
	Incorrect decisions (count)	2.17 (1.86)	1.67 (1.05)	3.00 (1.63)
	Number of pauses (count)	1.22 (1.81)	0.28 (0.45)	1.56 (1.89)

Note: SD = Standard deviation.

Table 5
Comparison of Performance for Group A and the Control Group.

Step	Indicator	Group A Mean (SD)	Control Group Mean (SD)	p
Step 3	Exploration time (sec)	603.28 (91.8)	532.72 (79.84)	0.022**
Step 4	Sketch score	20.83 (5.51)	16.78 (5.39)	0.074*
Step 5	Wayfinding time (sec)	351.33 (102.62)	398.94 (141.72)	0.293
	Incorrect path length (m)	102.38 (132.22)	159.73 (164.2)	0.308
	Incorrect path ratio	0.17 (0.17)	0.24 (0.19)	0.323
	Incorrect decisions (count)	2.17 (1.86)	3.00 (1.63)	0.143
	Number of pauses (count)	1.22 (1.81)	1.56 (1.89)	0.481

Notes: SD = Standard deviation; *marginal significant difference; **significant difference.

Table 6
Comparison of Performance for Group B and the Control Group.

Step	Indicator	Group B Mean (SD)	Control Group Mean (SD)	p
Step 3	Exploration time (sec)	599.72 (88.24)	532.72 (79.84)	0.044**
Step 4	Sketch score	21.33 (4.65)	16.78 (5.39)	0.019**
Step 5	Wayfinding time (sec)	313.11 (42.91)	398.94 (141.72)	0.118
	Incorrect path length (m)	47.89 (55.88)	159.73 (164.2)	0.017**
	Incorrect path ratio	0.10 (0.11)	0.24 (0.19)	0.017**
	Incorrect decisions (count)	1.67 (1.05)	3.00 (1.63)	0.011**
	Number of pauses (count)	0.28 (0.45)	1.56 (1.89)	0.034**

Notes: SD = Standard deviation; **significant difference.

than the average score of 16.78 for participants in the Control Group. The Mann–Whitney U test indicated that the results for the participants in Group A and the Control Group were only marginally significant ($U = 105.00$, $z = -1.81$, $0.05 < p = 0.074 < 0.1$), and the difference between participants in Group B and the Control Group was showed significant difference ($U = 88.50$, $z = -2.33$, $p = 0.019 < 0.05$). Therefore, the accuracy scores for all participants in the sketching map task indicated that the IAR-based navigation system can effectively improve the ability of participants to establish a cognitive map. However, no significant differences were found between the accuracy scores of participants in Group A and those in Group B, suggesting that the 3D layout model did not help the participants much in terms of developing cognitive map with the experimental environment ($p > 0.1$).

It can be noticed from Table 4 that the participants in the Control Group had the longest average time in the wayfinding task in Step 4. By comparing the p values for the incorrect path length ($p = 0.017 < 0.05$), the incorrect path ratio ($p = 0.017 < 0.05$), the number of incorrect decisions ($p = 0.011 < 0.05$), and the number of pauses ($p = 0.034 < 0.05$) in Tables 5 and 6, one can see that the differences between indicators in Group B and the Control Group were significant in terms of the incorrect path length and the numbers of incorrect decisions and pauses. However, the differences between Group A and Control Group for these indicators were not significant ($p > 0.1$).

By comparing the performance between the two groups that used IAR-based navigation devices (Table 7), it was found that although the overall wayfinding performance level for Group B is better than that for Group A, the difference between these two groups is far from significant. As such, it showed that a training process supported by an IAR-based navigation system that includes both superimposed guideposts and 3D layout models could significantly improve a user's performance in a later wayfinding task compared to the Control Group; however, the improvement when using such a system is not significantly better than that when using a system that only includes virtual guideposts.

3.2. Participants' workload in exploration and wayfinding tasks

The weights of all six factors in NASA TLX Workload Scale were calculated using a pairwise test, as shown in Table 8. It can be noticed that from the pairwise test results, the weights on physical workload and time pressure were fairly low. These results are expected, as this study focused on the mental workload and task performance of the participants.

Table 9 summarizes the scores for all six factors and the weighted average in both the exploration task (Step 3) and the wayfinding task (Step 5) for all three groups. The last two columns show the p values as well as the F values from an F-test. The average mental workload of participants in the Control Group was significantly higher than the average for participants in Group A and Group B. The LSD results indicated a significant difference both between Group A and the Control Group ($p = 0.034 < 0.05$) as well as between Group B and the Control Group ($p = 0.002 < 0.05$). In terms of task performance, participants in the two groups using an IAR-based navigation system gave their performance a better rating as compared to participants in the Control Group, but no significant difference was found. Similarly, participants in the Control Group reported that they made a greater effort and felt more frustration during the free exploration without a technological aid. The participants in Group A and Group B generated very similar weighted averages, and the weighted averages for these two groups were much lower than that for participants in the Control Group. The LSD test for the weighted average also proved a significant difference between Group A and the Control Group ($p = 0.021 < 0.05$) and between Group B and the Control Group ($p = 0.013 < 0.05$). It was safe to conclude that the participants in Group A and Group B had a lower overall workload than the participants in the Control Group during the exploration task (Step 3).

None of the three study groups showed any significant differences in mental workload or task performance during the wayfinding task (Step 5). One interesting finding was that participants in Group A claimed to have expended greater effort in the wayfinding task than participants in Group B ($p = 0.022 < 0.05$). Based on their self-reports, participants in Group B expended less effort in wayfinding than those in Group A ($0.05 < p = 0.065 < 0.1$). Participants in Groups A and B reported less frustration than participants in the Control Group, but the differences were not significant ($p > 0.1$). Weighted averages for the three groups indicated that participants in Group A and Group B experienced lower overall workloads than participants in the Control Group; however, the difference was not significant ($p > 0.1$).

Table 7
Comparison of Performance for Group A and Group B.

Steps	Indicators	Group A	Group B	p
		Mean (SD)	Mean (SD)	
Step 3	Exploration time (s)	603.28 (91.8)	599.72 (88.24)	0.888
Step 4	Sketch score	20.83 (5.51)	21.33 (4.65)	0.696
Step 5	Wayfinding time (s)	351.33 (102.62)	313.11 (42.91)	0.501
	Incorrect path length (m)	102.38 (132.22)	47.89 (55.88)	0.181
	Incorrect path ratio	0.17 (0.17)	0.10 (0.11)	0.181
	Incorrect decision (count)	2.17 (1.86)	1.67 (1.05)	0.650
	Pause (count)	1.22 (1.81)	0.28 (0.45)	0.214

Note: SD = Standard deviation.

3.3. Self-evaluation

The results of an analysis of the responses to the post-experiment questionnaire in terms of task difficulty and psychological anxiety are shown in Table 10.

For participants' anxiety, it is noted that participants in the Control Group felt more anxiety than participants in Group A and Group B, but the scores for overall anxiety level were moderately low, between 2.00 and 2.56 (where the maximum score is 5). Regarding the anxiety reported for the wayfinding task (Step 5), participants in Group B demonstrated less anxiety compared to those in the other two groups. For confidence factor, participants equipped with the IAR-based navigation system indicated that they felt more familiar with the environment after the exploration task. Participants in the Control Group indicated that they had more difficulty in completing the exploration task (Step 3) and the sketch map task (Step 4) than those in Group A and Group B, though the difference was not significant. Meanwhile, there was no obvious difference between the three groups in terms of their assessment of the difficulty in completing the wayfinding task (Step 5). However, none of the results were significant (all $p > 0.1$) with the exception of Q4, the question regarding the difficulty in completing the exploration task. For Q4, a Mann–Whitney U test confirmed the significant difference between Group A and the Control Group ($U = 236.00$, $z = 2.44$, and $p = 0.019 < 0.05$) and between Group B and the Control Group ($U = 236.00$, $z = 2.44$, and $p = 0.019 < 0.05$), which suggested that the IAR-based navigation system significantly lowered the participants' difficulty in completing the exploration task (Step 3).

The results of the survey questionnaire designed to evaluate the usability of the HMAR device is shown in Table 11. Participants in both Group A and Group B were clearly able to master the operation of the HoloLens, and they successfully completed the tasks in this experiment, based on their overall performance; however, they did not give high marks to the HMAR device regarding the ease of use. The responses to Question 3 (Q3 in Table 3) were used to examine whether the HoloLens could effectively help people to complete the exploration task, and it was confirmed by participants in both Group A and Group B that the device was effective. The Mann–Whitney U test for the response to Question 4 (Q4 in Table 3) indicated that the IAR-based navigation system with 3D layout models in addition to guideposts could significantly improve the establishment of cognitive maps as compared to the IAR-based

Table 8
Weights of Factors in the NASA TLX Questionnaire.

Factor	Mental Workload	Physical Workload	Time Pressure	Task Performance	Effort	Frustration
Weight	5	0	1	4	2	3

Table 9
NASA TLX Scores for the Exploration Task (Step 3) and Wayfinding Task (Step 5).

Step	Factor	Group A Mean (SD)	Group B Mean (SD)	Control Group Mean (SD)	*p* value	*F* statistic
Step 3	Mental Workload	9.83 (3.48)	8.44 (4.34)	12.67 (3.51)	0.007**	5.457
	Physical Workload	5.78 (3.57)	6.44 (3.06)	6.33 (2.43)	0.793	0.233
	Time Pressure	4.61 (3.39)	4.94 (2.99)	6.22 (2.90)	0.287	1.281
	Task Performance	13.11 (4.01)	12.06 (4.01)	10.94 (4.85)	0.349	1.076
	Effort	10.11 (3.60)	10.11 (4.45)	12.56 (3.37)	0.110	2.303
	Frustration	4.44 (3.44)	4.17 (4.02)	6.67 (4.85)	0.166	1.859
	Weighted Average	7.66 (2.38)	7.44 (3.36)	10.06 (3.02)	0.022**	4.124
Step 5	Mental Workload	11.17 (4.39)	9.89 (5.53)	10.83 (4.03)	0.714	0.339
	Physical Workload	8.11 (4.23)	6.33 (3.62)	7.44 (3.83)	0.413	0.901
	Time Pressure	7.61 (5.17)	5.83 (3.75)	7.44 (4.50)	0.452	0.807
	Task Performance	12.39 (5.11)	11.89 (5.07)	11.44 (4.95)	0.862	0.149
	Effort	12.61 (4.67)	9.17 (3.80)	11.39 (4.21)	0.065*	2.883
	Frustration	6.67 (5.25)	6.00 (4.73)	8.00 (4.42)	0.472	0.762
	Weighted Average	9.27 (3.87)	8.27 (4.10)	9.51 (3.50)	0.609	0.501

Note: *Marginal significant difference; **Significant difference.

Table 10
Analysis Results for Responses to the Post-experiment Questionnaire.

Factor	Question	Group A	Group B	Control Group
		Mean (SD)	Mean (SD)	Mean (SD)
Anxiety	Q1	2.11 (1.10)	2.00 (0.94)	2.56 (1.21)
	Q7	2.50 (1.21)	2.28 (1.04)	2.61 (1.01)
Confidence	Q2	3.33 (0.94)	3.39 (0.83)	3.00 (0.94)
	Q3	3.33 (1.05)	3.61 (0.89)	3.11 (0.87)
	Q6	3.89 (1.05)	3.67 (0.94)	3.72 (0.93)
Difficulty	Q4	2.22 (1.08)	2.33 (0.88)	3.22 (1.13)
	Q5	3.78 (1.03)	3.61 (0.95)	4.00 (0.82)
	Q8	2.72 (0.99)	2.72 (1.10)	2.67 (1.20)

Table 11
Result of HoloLens Usability Evaluation Survey.

Type	Question	Group A	Group B
		Mean (SD)	Mean (SD)
Efficiency	Q1	3.67 (0.94)	3.83 (1.01)
	Q2	4.50 (0.69)	4.39 (0.68)
Effectiveness	Q3	4.11 (0.66)	4.39 (0.76)
	Q4	3.72 (0.80)	4.33 (0.82)
Satisfaction	Q5	4.39 (0.68)	4.61 (0.49)
	Q6	4.44 (0.60)	4.50 (0.60)
	Q7	4.11 (0.74)	4.39 (0.59)

navigation system that included guideposts only ($p = 0.031 < 0.05$, $U = 230.00$, and $z = 2.29$). All HoloLens users gave high marks in Questions 5 through 7 (Q5, Q6, and Q7 in Table 3), which indicated that they all had a positive attitude towards high-technology products (the average scores of these three questions are all above 4).

4. Discussions

Before the discussions, a summary table was used to help the understanding of the results. As summarized in Table 12, the results of the NASA TLX questionnaire and the experimental evaluation questionnaire in Step 3 showed that the IAR-based navigation system significantly reduces the overall workload of the participants in free exploration task and also significantly reduces their perception of the difficulty in completing the task.

In terms of overall wayfinding performance during Step 5, participants in Group B had the best performance, followed by participants in Group A, and those in Control Group had the worst performance. Several wayfinding performance indicators such as incorrect path length and rate, number of incorrect decisions, and number of pauses, of participants in Group B were significantly better than those of Control Group, and participants in Group B were also more accurate in drawing layout sketches. This indicates that, compared to the IAR-based navigation system A, the IAR-based navigation system B equipped with 3D layout models may release the potential of AR technology to a greater extent.

4.1. Effect of guideposts in an IAR-based navigation system

According to the results, although the IAR-based navigation system with guideposts increased the exploration time for the participants (Table 5), it was able to significantly reduce the workload by 23.86% (Table 9) and task difficulty by 31.06% (Table 10) compared with those in the free exploration process without navigation system. Moreover, the IAR-based navigation system with guidepost was able to effectively enhance the establishment of cognitive maps by 24.14% compared with the Control Group according to the results of sketch score (Table 5).

One possible reason for these findings is that the IAR-based navigation system with guidepost provided the route knowledge (the ability to

Table 12
Summary of significant variables measured in Step 3 and Step 5.

Group	Group (To Be Compared)	Significant Variables in Different Steps	
		Step 3	Step 5
Group A (Guidepost only)	Control Group	Make the task easier Lower the workload	Strengthen the cognitive map
Group B (Guidepost plus 3D layout model)	Control Group	Make the task easier Lower the workload	Strengthen the cognitive map Reduce incorrect path Reduce incorrect path ratio Reduce incorrect decision Reduce the number of pauses
	Group A	N/A	Reduce the effort in wayfinding Help build a cognitive map

learn the way from one point to another by following a fixed sequence of turns), which was more conducive to establishing a higher level of spatial cognitive map in the participants. Route knowledge is the second stage of the spatial cognition according to spatial cognitive microgenesis [67]. The main idea of this theoretical framework is that an individual's cognitive map development in a new environment should go through the following three stages in succession: landmark knowledge, route knowledge, and survey knowledge. Route knowledge includes the order of the landmarks and information about how to connect the landmarks in the environment [68]. Herman et al. [69] found that individuals can acquire landmark knowledge immediately when exposed to an unfamiliar environment, while an improvement in route knowledge only occurs after a few sessions of learning. The IAR-based navigation system that included guideposts directly provided the participants with the route knowledge required in the exploration, and the participants were able to develop a higher stage in their overall cognitive maps based on the navigation systems and active learning of the environment, which greatly reduced the mental load required for the exploration process as well as the workload in the cognitive mapping process.

Moreover, in contrast to the findings of previous studies that found mobile navigation was detrimental to the development of spatial cognitive maps [24,25], this study showed that IAR-based navigation systems using a guidepost could positively facilitate the development of a spatial cognitive map. This was probably because that, when using a HMAR device, the participants did not need to shift their attention back and forth between the environment and the navigation system, which would otherwise require considerable cognitive effort on the part of the participants using the device. Instead, the route knowledge was directly displayed by the IAR-based navigation system, leading to decrease in participants' self-reported task difficulty and mental load, which was aligned with findings reported in previous research [34]. Although the exploration time was increased by the use of the navigation system, it was mainly due to the time required to scan QR codes during the exploration task, which was only needed during the training stage and could become unnecessary with future improvements to the technology. On the whole, when facilitated by an IAR-based navigation system, participants were able to establish effective spatial cognitive maps. This corroborated previous research that found that AR has the potential to help humans improve the quality of tasks [33]. In addition, the high usability assessments reported by the participants (Table 11) suggested that the IAR-based navigation system would have a desirable level of adoptability, and its values observed in this study may have good potential to be realized in practice and benefit various application scenarios where navigation service for cognitive map development is needed, such as a guidance system for vehicle drivers or a wayfinding aid for firefighters during indoor emergency response operations.

4.2. Effect of 3D layout models in an IAR-based navigation system

To explore the effect of the 3D layout models on human wayfinding performance and the development of cognitive maps, a 3D layout model was integrated into guidepost of IAR-based navigation system. The results showed that incorporating a 3D layout model along with the guideposts in the IAR-based navigation system increased the exploration time in the process (Table 6) but could significantly reduce participants' workloads by 26.04% (Table 9) as well as the difficulty of the task by 27.64% compared with those without navigation system in the process of exploration (Table 10). The IAR-based navigation systems incorporating a 3D layout model along with the guideposts could effectively enhance the development of cognitive maps by 27.12% according to the sketch map score (Table 6), effectively reducing incorrect path length by 70.02%, the number of incorrect decisions by 58.33%, the ratio of incorrect path by 44.33% and the number of pauses by 82.05% in the process of wayfinding compared with Control Group (Table 6). As a result, the wayfinding performance of the participants could be improved. This is made evident by the fact that, using the data from the Control Group as a baseline, a few additional indicators that measured the development of cognitive maps and the wayfinding performance showed more significant improvement in Group B than in Group A, as shown in Tables 5 and 6.

One possible reason for the observed differences in the extents to which cognitive maps development and wayfinding performance were improved is that the use of 3D models directly provided the participants with the survey knowledge needed in the exploration and wayfinding process. According to the spatial cognitive microgenesis theory mentioned previously, the highest stage of a cognitive map is the survey knowledge that integrates landmarks, routes and other information in the environment into an overall, map-like spatial layout. It is important to emphasize that the establishment of complete survey knowledge is complex and difficult. In the wayfinding process, route knowledge and related information in the environment are subsequently integrated into more complex overall knowledge, and the integration process is subtle and complex [67]. Some researchers have even found that the survey knowledge of individuals comes from physical maps, while only route knowledge can be acquired through direct experience [70,71]. In addition, existing research indicates that it is difficult to effectively establish a complete cognitive map for an indoor environment because the environment is divided into fragmented pieces, and people are unable to view the environment from a global perspective [72]. In this experiment, the participants could directly obtain the survey knowledge about the environment according to the 3D layout model rendered in the space and navigate to the destination directly according to the guideposts, without having to do much cognitive processing. In addition, the HMAR devices used in the IAR-based navigation system could significantly reduce human mental workload, according to the experimental results related to the subjective mental load assessment in Table 9 and the self-reported difficulty of the task in Table 10. This was consistent with a recent study, which assessed mental load using hemodynamic measures and reached same conclusion [35]. Although the scanning of QR codes increased the exploration time when using the navigation system, the HMAR users might have no need for complex cognitive processing in terms of obtaining an accurate spatial cognition map. Based on such a spatial cognitive map, these participants showed high performance and low error decision rates in the later wayfinding process.

A direct comparison between the self-reported results for Group A and Group B (Table 11) show that the 3D layout models were significantly helpful to improve the establishment of participants' cognitive maps. This finding was consistent with those reported in previous research, which found that the addition of 3D layout maps to a navigation system would help to enhance the development of cognitive maps [27]. However, the results also suggested that there was no significant difference in terms of the cognitive map development and wayfinding performance between the participants in Group A and Group B, as measured by a number of objective indicators that are summarized in Table 7. One possible reason for a lack of significant differences between the two groups could be that the 3D layout models directly provided all orientation, position, and other information to the participants, which might have taken over some of the participants' cognitive processes such as positioning, the planning of routes, spatial updating, and the process of identifying directions [73]. As a result, the participants did not need to actively process the spatial information, and this could have affected their ability to retrieve and utilize the information when it was needed. Meanwhile, the study participants who were provided with only guidepost information were able to learn more actively on their own, which to some extent mitigated the disadvantage of not having direct access to the spatial information embedded in the 3D layout models. Hence, the addition of a 3D layout model brought advantages that did not significantly impact the participants' cognitive map development and wayfinding performance as compared to an IAR-based navigation system that included only the guideposts.

4.3. Practical implications

We have identified that there are great improvements in both wayfinding performance and development of cognitive map for participants using the IAR-based navigation systems compared with those without IAR-based navigation systems. These improvements achieved by the IAR-based navigation systems might make substantial differences in certain use cases where system users aim to develop cognitive maps efficiently and accurately. Such potential users include pilots, vehicle drivers and firefighters. The IAR-based navigation system could be used as the training tool for them to develop the cognitive maps. For pilots and drivers, Furukawa et al. [20] reported that after the cognitive map training, pilots and drivers were able to become familiar with external environments faster and reduce mental load on navigation. For a firefighter, it is necessary to develop the cognitive map in daily training because they often predict the spatial outcome of the current building based on the spatial knowledge of buildings with similar features during the rescue [21]. Developing a cognitive map can reduce the time they spend on the arriving the site and remembering the escape route [74]. On the other hand, due to the difficulty of using the HMAR, it takes more time for users to perform the exploration task when using these navigation systems. The IAR-based navigation systems with the 3D layout model in addition to the guidepost could improve the wayfinding performance. With the development of indoor positioning techniques, the time spent on scanning the QR code could be saved. The IAR-based navigation systems also may have the potential to be used to explore new places in everyday life.

For usability, the results have been summarized in Table 11. The participants in Groups A and B could quickly master the operation of HoloLens and successfully completed the tasks in this experiment with the IAR-based navigation system and acknowledge the effectiveness of the IAR-based navigation system. All HoloLens users had positive attitude towards this high-technology product. In informal post-experiment interviews, the participants suggested that the IAR-based navigation systems, which helped them become familiar with and remember the interior layout of the building during the experiment, had significant potential to be used as a guide system for navigation aid in daily life or as a cognitive map training tool in emergency drills. Meanwhile, the participants were not enthusiastic about the ease of use of the HMAR device, mainly because they found it difficult to scan the QR codes through the HMAR, a technical limitation of the system that should be addressed in the future.

In addition, there are four prospects of developing better IAR-based navigation systems that can be derived from the findings of this study. First, the new navigation mode that integrated 3D layout models and guidepost was tested and proved to be beneficial to build human cognitive maps. This new mode could be adopted to develop a more effective and useful IAR-based navigation system. Second, the need to scan the QR codes in the experiment was a major contributor to participants' limited ratings of the usability of IAR-based navigation systems. This suggested that some form of markerless tracking technology [75] should be integrated to develop a more adaptive and user-friendly IAR-based navigation system. Third, manually tracking and recording participants' behavior, as was done in this study, required significant manpower and could involve human errors. In the future, some form of automatic data collection technology could be integrated into the IAR-based navigation system to solve this problem. Fourth, participants' mental load was measured only using the subjective method in this study. This assessment could only be done after the navigation and could be potentially biased because of the tendency of participants to present themselves in a generally favorable fashion according to prior research [76]. This suggested that physiological assessment methods, using physiological sensors such as the eye-tracker, could be used in developing future IAR-based navigation systems, so as to monitor users' mental load in real time and avoid information overload during the navigation process.

4.4. Limitations and future research

This study bears several limitations that are noteworthy. First, the experimental participants only included university students who were relatively young (average age of 22) with a relatively high level of education. The impact of IAR-based navigation systems on wayfinding training concluded in this study could be different for individuals who are older or younger or individuals who are better or less educated than those in our study group. This is because age and educational level could play important roles in wayfinding, as has been suggested by other studies [17]. For example, there was evidence of age-related differences in the acquisition of configural knowledge in spatial navigation [77]. Hence, people with more diverse demographic attributes should be investigated in future research to test and improve the generalizability of the findings of this study. Second, due to the technical limitations in providing accurate indoor positions, our IAR-based navigation systems adopted QR code anchors as an alternate solution. This notably reduced the ease of use of the system, as the participants had to operate HoloLens to scan QR codes periodically. To realize real-time indoor positioning in an IAR environment, it is suggested to integrate an accurate indoor positioning system with HMAR devices. This future trend suggested by the findings of this study also fits with previous research which suggested that HMAR needs to become more comfortable and powerful, and the tracking robustness needs to be improved [78]. Third, the experimenter manually tracked and recorded the participants' wayfinding time, extra path length, number of incorrect decisions and number of pauses during the experiment. These manual measurements might involve a certain level of inaccuracy and bias. A new data collection system should be developed that is adaptive to different use scenarios and capable of collecting various behavioral data of participants for intended research purposes. Such a future trend revealed in this study echoes the findings of previous research that also posited that future AR systems must be adaptive and should be able to systematically collect user data [78]. Lastly, the single-story indoor environment used in this study had a large area and a relatively complex layout. However, vertical navigation was not investigated in this study. In future research, multi-story buildings with more complex layouts should be used to examine whether findings of this study would still be valid when people navigate around vertical spaces.

5. Conclusions

In this study, a new indoor IAR-based navigation system with a guidepost and a 3D layout model was developed. The system was tested to investigate the effect of the 3D layout models in addition to superimposed guideposts in IAR environments on human performance in indoor wayfinding and cognitive map development. A total of 54 participants were assigned to three groups: one provided with HMAR devices using an IAR-based navigation system that included only guideposts, one provided with HMAR devices and an IAR-based navigation system that included both guideposts and 3D layout models, and participants in a control group that did not use HMAR devices. All participants were required to freely explore an indoor environment having a fairly complex layout. After sketching the layout of the environment based on memory, the participants were asked to perform a wayfinding task without any aid. Two NASA TLX questionnaires were completed—one after the exploration task and one after the wayfinding task—to examine the workload of these two tasks. Finally, a post-experiment survey was conducted to understand opinions from participants about the experiment and the HoloLens. Knowledge about this effect will lead to IAR-based navigation systems that are better engineered and more adaptive for different use cases.

Two major results of this research were reported in terms of wayfinding. First, an analysis of data for the observed wayfinding performance indicates an IAR-based navigation system can enhance the development of the participants' cognitive maps through superimposed information and, in turn, substantially improve their wayfinding performance. Second, it confirms that 3D layout models are important for enhancing the development of cognitive maps when superimposed onto guidepost information. The results of the post-experiment survey also indicate that people are interested in HMAR devices in general, though these devices still have much room for improvement in terms of comfort. These findings compensate for the gap in knowledge in which the impact of IAR-based systems on human wayfinding performance from a cognitive perspective has not previously been a focus. The research findings also indicate that the modes of guidepost and the 3D layout models superimposed onto the user's view of a real-world scene by the HMAR could be used in future navigation systems for users who need to develop cognitive maps, as this mode has rarely been adopted by engineers to develop better IAR-based navigation systems. The findings also revealed that further research and analysis on indoor positioning technology and the effect of IAR-based navigation systems on different user groups in more complex spaces with different layouts are necessary to identify appropriate navigational aids for supporting both cognitive map training and wayfinding aids.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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