# The effects of 2D and 3D maps on learning virtual multi-level indoor environments

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# The Effects of 2D and 3D Maps on Learning Virtual Multi-level Indoor Environments

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## ABSTRACT

It is known that people have problems when wayfinding in multi-level buildings. We propose that this challenge is largely due to development of inaccurate multi-level cognitive maps of the 3D building structure. We argue that better visualization of the layered structure of the building could facilitate multi-level cognitive map development and significantly improve spatial behaviors requiring cross-floor knowledge. To address this issue, we compare two viable mobile digital visualization methods (2D top-down view maps and 3D bird's eye view maps), each showing users' real-time position as they navigated. Participants first learned a multi-level virtual building using each of these conditions, as well as a third control (non-assisted) condition. Their task was to find and learn four targets situated at two different landmark types (e.g., contiguous landmarks that were vertically aligned on each floor and non-contiguous landmarks that had no obvious alignment between floors). Participants then took part in three cross-level testing tasks performed without the map assistant used during learning: pointing between targets, vertical navigation (e.g., navigate from point A on floor 1 to the corresponding vertically aligned point on floor 2) and paper-based drilling (e.g., drawing circles to indicate floor 1's target locations on floor 2's layout). Preliminary results showed that both 2D and 3D map significantly improved pointing and vertical navigation accuracy compared to the control condition with no map assistance. However, no significant differences were found for either condition between the two map conditions. By contrast, in the paper-based drilling task, users showed significantly higher accuracy in the 2D map condition than in both the 3D map and control conditions, giving 2D interactive maps the advantage for supporting multi-level spatial behaviors.

## Categories and Subject Descriptors

H.1.2 [**User/Machine Systems**]: Human factors; H.5.1 [**Multimedia Information Systems**]: Artificial, augmented, and virtual realities; H.5.2 [**Information Interfaces and Presentation**]: User Interfaces

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## General Terms

Design, Experimentation, Human Factors

## Keywords

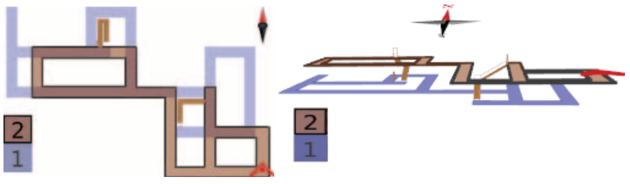
Indoor wayfinding, multi-level cognitive map, map viewpoint, indoor landmarks

## 1. INTRODUCTION

Most travelers have an unpleasant story about a building that they dislike because they often become disoriented or get lost in it. In some hospitals, patients are even reluctant to leave their rooms as they fear that they will not find their way back [14]. These buildings usually have a complex multi-level structure with many above ground floors and underground levels. Previous literature has demonstrated that indoor wayfinding performance involving floor level changes is greatly hindered by disorientation during vertical travel [16]. Likewise, Holscher and colleagues reported wayfinding difficulties observed in a complex multi-level conference center, identifying incongruent floor layouts, disorienting staircases, and lack of visual access to important level-related building features as the main causes of this difficulty [6]. On average, people spend 87% of their time in indoor spaces [8]. Much of this time requires successfully finding one's way around public buildings across multiple floors; these cross-level navigation behaviors could be greatly helped by having an accurate multi-level spatial representation of the buildings (e.g., a cognitive map). However, cognitive maps have a very general definition, referring to an animal/human's allocentric knowledge of spatial and environmental relations [7]. It is widely accepted that cognitive maps are used to understand the environment and make spatial decisions. However, most research regarding cognitive maps is based on single-plane outdoor space or one floor of a building and little research has focused on development of multi-level spatial representations of the environment, as from complex multi-floor indoor spaces. We refer to this type of spatial representation as a multi-level cognitive map [10]. Multi-level cognitive maps would particularly help with tasks and spatial behaviors requiring cross-floor knowledge, e.g., cross-floor pointing, navigation, and spatial alignment of locations between floors. Thus, we argue that possessing an accurate multi-level cognitive map of complex indoor environments would greatly benefit users in supporting navigation, inferring new routes, and taking shortcuts between floors and thereby plays an important role in multi-level indoor wayfinding that has not been discussed in the literature.

Previous literature has discussed that the horizontal and angular transition offsets between floors also cause users to have greater difficulty in maintaining their spatial orientation and in developing an accurate multi-level cognitive map of the indoor space [10]. Poor visual access between floors due to occlusion from walls and ceilings further hinders the development of accurate multi-level cognitive maps. It is obviously impractical to modify the physical building structure to improve visual access between floors and traditional You-Are-Here maps cannot provide navigators with information about their real time position and orientation as they move, which has been found to significantly benefit wayfinding performance [13]. Therefore, this paper focuses on evaluating visual interfaces on mobile devices used during real-time indoor wayfinding. We propose that increasing visual access to the building's layered nature (e.g., multiple floors) by use of interactive maps will have a positive effect on the development of more accurate multi-level cognitive maps and consequently promote significantly better cross-level wayfinding performance. This hypothesis was tested on several behavioral tasks requiring cross-floor spatial knowledge, e.g., between-floor connectivity information and vertically aligned spatial knowledge.

Most currently available indoor mobile digital maps supporting real time indoor navigation, e.g., Google Indoor map, indoor OpenStreetMap, etc., can only show one floor at a time, meaning users can only obtain visual access to individual floors and thus have no direct means for integrating knowledge between floors. Although prevalent, this type of map requires that users must manually integrate spatial knowledge between multiple layers over time, and this temporal and spatial integration is likely hard, inaccurate, and leads to errors, as one's spatial representation of the buildings may be coherent locally but not globally [1, 5]. Therefore, there is a significant need for us to explore the optimal visualization techniques to facilitate multi-level cognitive map development. In this study, we proposed and evaluated two visualization methods (2D map with a top-down viewpoint vs. 3D map with a bird's eye viewpoint) as shown in Figure 1, compared to a control condition (without map assistant). Our two visualization approaches are different from the traditional single-floor map visualization method in that both show multiple floors at the same time and provide users with access to their alignment (or mis-alignment) in a straight forward manner as the user moves through the space.



a. 2D top-down viewpoint b.3D bird's eye viewpoint

**Figure 1. Two maps for multi-level buildings**

The first research question addressed in this paper asks whether the map view perspective (2D top-down view map vs. 3D bird's eye view map) affects the development of multi-level cognitive maps. Several studies have investigated the pros and cons of using 2D and 3D visualizations on portable mobile displays in assisting navigation in both outdoor and indoor spaces [2, 11, 12]. As for outdoor space, Oulasvirta et al. [12] found users assisted with 2D maps were able to extract more information in less time and used reliable and ubiquitous environmental cues like street names and crossings more frequently than 3D maps; compelling empirical evidence found in their research showed that a 2D street map can outperform a 3D mobile map. However, the 3D map in their research meant a photorealistic representation of the real world (2.5D), as outdoor environments are only composed of a horizontal plane providing no alignment or connectivity information between different planes. In our study, the 3D bird's-eye view maps afford simultaneous access to multiple floors/planes. We aim to investigate whether this type of 3D map could outperform a 2D map for assisting multi-level cognitive map development in these true 3D (i.e., multi-level) indoor environments.

Chittaro et al. [3] evaluated 2D maps vs. 3D maps for assisting navigation in a multi-level virtual building and the 2D map also outperformed the 3D interface for assisting users to find three object targets whose locations were indicated by a navigation aid. However, in their research, users were assisted by the maps while they were looking for the targets and the target locations were indicated on the maps. By contrast, in the current research, participants were only assisted with the digital maps for visualization during the learning phase, as we aimed to investigate whether their use facilitated development of multi-level cognitive maps that supported subsequent behavior on cross-floor tasks during testing. Additionally, most users only learned the 3D maps from a fixed viewpoint in the Chittaro study, as only one participant made use of the sliders to change the map orientation. To solve this problem in our research, the system automatically rotated the 3D bird's eye viewpoint when users passed by the targets; this allows users to learn the building from multiple perspectives, as shown in Figure 2.

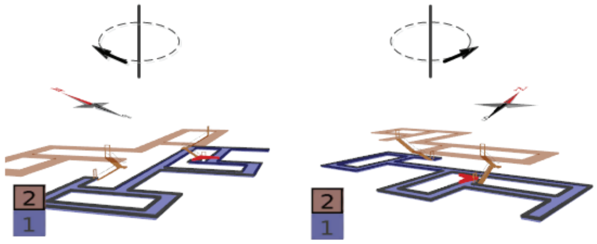


**Figure 2. Rotation of the 3D bird's eye viewpoint**

The second research question addressed by this paper asks how different landmark types (contiguous landmarks that were vertically aligned on each floor and non-contiguous landmarks that had no obvious alignment between floors) might affect performance of cross-level learning and multi-level cognitive map development. Li & Giudice [10] proposed the term "contiguous landmark" in the multi-level indoor environment referring to vertically aligned indoor landmarks, which consist of a set of vertically aligned structural or object landmarks located on different floors. For instance, two vertically aligned blue walls can be conceptualized as a contiguous object landmark; while two vertically aligned T intersections can be conceptualized as a contiguous structural landmark. The vertical alignment is salient, so could in theory be "glue" to align the floors. Although each part of the contiguous landmark is usually perceived discretely on each floor, the maps make them perceptually available as users can directly visualize the relation between floors and learn the alignment without the normal spatiotemporal constraints and other limitations that usually limit access to cross-floor information integration. Therefore, we propose that contiguous landmarks could help multi-level cognitive map development, as they provide a common frame of reference to consolidate the individual floor knowledge into a consistent building-level mental framework.

# 2. METHOD

## 2.1 Participants

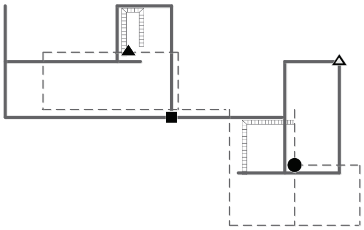
Eighteen participants (9 female and 9 male, mean age=25.8, SD=7.4) were recruited from the University of Maine. All participants self-reported as having normal or corrected to normal vision (no color blindness). All gave informed consent and received monetary compensation for their time.

## 2.2 Materials and Apparatus

A Lenovo W510 Thinkpad 15.6-inch workstation notebook with an Intel Core i7 processor and NVIDIA Quadro FX 880M graphics was used. A Logitech Extreme 3D Pro Joystick was used to perform both translational and rotational movements (see [9] for a comparison of VE platforms showing efficacy of this movement behavior in similar multi-level indoor environments as are used here.). As shown in Figure 3, our environments were comprised of three two-level virtual buildings which were designed using Revit Architecture 2013 (AutoDesk, Inc). The Unity 4.0 VR engine (Unity Technologies) was used as the VE platform supporting users' real-time navigation and recording their trajectory and test performance.

**Figure 3. Virtual Environments (multi-level building) with a simulated mobile device.**

All three buildings have the same number of corridors and intersections, meaning the layout topology and complexity between buildings was equated. As shown in Figure 4, the solid and dashed line respectively represents the first and the second floor layout. Two vertically aligned T intersections were used to represent a contiguous structural landmark, while two vertically aligned chandeliers were used to represent contiguous object landmarks. In addition, two non-contiguous single-floor landmarks (an L intersection and a doorway) were used in each virtual building. As shown in Figure 4, ● represents target A located at a contiguous object landmark; ■ represents target B located at a contiguous structural landmark; ▲ represents target C located at a doorway; △ represents target D located at an L intersection**.** Users could move in the virtual building by the joystick at a fix speed (6m/s forward/backward, 3m/s sideways).



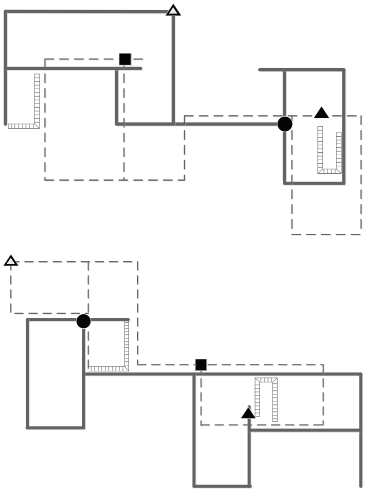


**Figure 4. Floor layouts with target locations denoted**

The start learning point was located at the southeast corner of the building. There was a red arrow in the virtual building indicating the start point and the north direction. The two floors were connected by two staircases. There were two pictures on each floor which served as experimental targets. Pictures were based on four high imagery words: chair, table, bottle and clock. The four targets were located at two types of landmarks as shown in Figure 4. The targets were initially hidden from view but when participants passed the target, an audio signal was triggered that gave its name. The target also visually appeared for ten seconds and then faded out.

## 2.3 Procedure

A within-subject design was adopted, with eighteen participants running in all three conditions. There were seven phases in the experiment.

Phase 1: *practice*. Participants were familiarized with the apparatus and navigation behavior in a practice virtual building. All experimental tasks were explained and demonstrated before starting the experimental trials.

Phase 2: *environmental learning*. Participants freely learned the building for six minutes using a user-defined open search procedure. From a north orientation at the learning start point. They were asked to find all four targets and remember their relative directions to each other and the building's configuration as a whole. All participants successfully found all four targets within the learning period.

Phase 3: *pointing task*. Participants were set to either the contiguous object landmark or contiguous structural landmark in the virtual building and asked to turn to face another target. They were asked to face the direction that makes a straight-line between targets, ignoring the walls or paths to walk the route between them. To perform the task, participants must rotate in place and click the joystick's trigger when they thought they were facing the correct direction of the destination target. If the targets were located on different floors, they were instructed to ignore the height offset and point as if the targets were on the same plane as the floor they were currently on. Accurate pointing required them to make Euclidean judgments from one target to the other target.

Phase 4: *navigation task*. Upon completion of the pointing phase, participants were automatically set at either the contiguous object landmark or contiguous structural landmark and asked to navigate between targets using the shortest path. The navigation results will not be discussed in this paper as route knowledge accuracy is not related to our principle interest of integration of vertical knowledge.

Phase 5: *vertical Navigation task*. Participants were set to one target location and given its name. Their task was to navigate to the corresponding point in the environment that was directly above or below the target at which they were currently located. For example, if participants were located at target chair on the ground floor, their task was to navigate to the corresponding point on the second floor that was directly above chair. In each building, there is one target that is located at a place where there is no corresponding point on the other floor's corridor. In this case, they were asked to navigate to the location that was closest to the corresponding vertically-aligned point.

Phase 6: *paper-based drilling task*. In this task, participants were first given a paper which showed the first floor layout. The experimenter provided the targets' names of the second floor. The task was to draw circles on the first floor layout to indicate the horizontal locations of the targets located on the second floor. Next, participants were given the second floor layout and asked to indicate the first floor targets using the same method.

Phase 7: participants took part in a user preference survey.

# 3. RESULTS

## 3.1 Pointing Task

The pointing error was subjected to a two-way repeated measures ANOVA having three levels of visualization method (2D top-down viewpoint, 3D bird's eye viewpoint and no map assistant) and two types of landmarks(contiguous landmarks vs. non-contiguous landmarks). As is shown in Figure 5, the participants in the control condition (where no map assistance was available) showed significantly higher absolute error (M=87.6º, SE= 9.4º) than those in the 2D map condition (M=67.0º, SE=9.9º) and 3D map condition (M=62.4º, SE=7.9º), *F*(2, 34) = 42.483, *p* < .001. There was no significant difference for landmark type (contiguous landmarks vs. non-contiguous landmarks), *F*(1, 17)=1.663, *p*=0.214. There were no significant interaction effects between visualization method and landmark type.

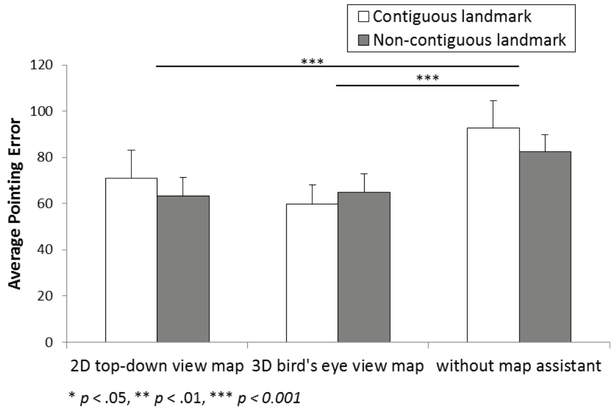


**Figure. 5. Comparison of average pointing error (± SEM) for the three levels of visualization method**

## 3.2 Vertical Navigation Task

The vertical navigation accuracy data was subjected to a two-way repeated measures ANOVA having three levels of visualization method and two types of landmarks. The main effect of visualization method was significant, *F*(2, 34) = 3.433, *p* < .01, indicating that the average vertical navigation accuracy was significantly better for the 2D map (M=40.3%, SE=7.6%) and 3D map conditions (M=43.1%, SE=6.9%) than for the control condition (M=26.4%, SE=7.1%). The main effect of landmark was not significant, *F*(1, 17) = 1.889, *p* = .187. There were no significant interaction effects between visualization method and landmark type.

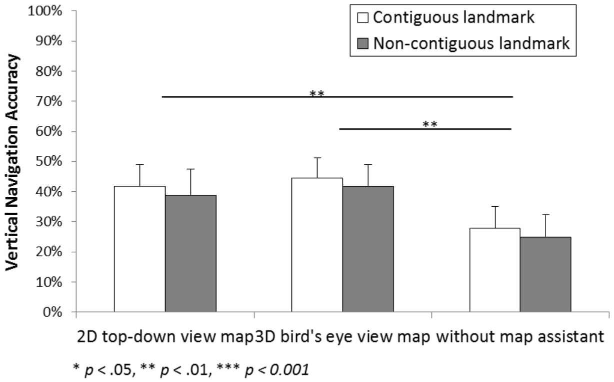


**Figure. 6. Comparison of vertical navigation accuracy (± SEM) for the three levels of visualization method**

## 3.3 Paper-based drilling Task

The drilling accuracy was subjected to a two-way repeated measures ANOVA having three levels of visualization method and two types of landmarks. The main effect of visualization method was significant, *F* (2, 34) = 8.859, *p* < .01, indicating that the average drilling accuracy was significantly higher for the 2D map (M=25.0%, SE=8.8%) than for the 3D map conditions (M=11.1%, SE=6.1%) and the without map assistant condition (M=9.7%, SE=5.0%). The landmark type variable was not significant, *F*(1, 17) = 1.889, p = .187. However, there was a significant interaction between visualization method and landmark type, *F* (2, 34) =3.923, p < .05. Post hoc comparisons indicated that users found more accurate targets at contiguous landmarks in the 2D top-down view map condition (M=30.6%, SE=10.0%) than in the 3D bird's eye view map condition (M=8.3%, SE=4.5%). These results indicate that the 2D top-down view map is the most efficient for assisting the drilling task, which requires an accurate multi-level cognitive map to perform accurately.

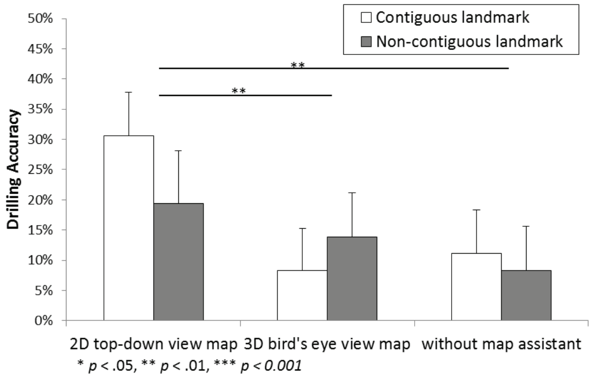


**Figure. 7. Comparison of drilling accuracy (± SEM) for the three levels of visualization method**

The 2D top-down view map condition consistently outperformed the without map assistant condition in all three tasks. To further investigate whether some subjects consistently performed better in all three tasks, two linear regression analyses were conducted to test if the drilling accuracy performance, which we consider the strongest measure of cross-floor integration, significantly predicted participants' pointing and vertical navigation performance. The results of the regression indicated drilling performance significantly predicted pointing error, $\beta = -.63$, $t(16) = -3.245$, $p < .005$, and drilling performance explained a significant proportion of variance in pointing errors, $R^2 = .397$, $F(1, 16) = 10.529$, $p < .005$. Drilling performance also significantly predicted vertical navigation accuracy, $\beta = .584$, $t(16) = 2.881$, $p < .011$, and explained a significant proportion of variance in vertical navigation accuracy, $R^2 = .342$, $F(1, 16) = 8.302$, $p < .011$. Therefore, users' drilling performance was significantly related with the pointing and vertical navigation performance, which we interpret as indicating that all three tasks require spatial knowledge that benefits from accurate development of multi-level cognitive maps. The reliably better performance of the 2D top-down view map suggests that this visualization method may be the best solution for promoting development of multi-level cognitive maps.

## 3.4 User Preference Survey

Corroborating the statistical advantage observed for the 2D maps, fourteen participants indicated that they preferred the 2D top-down view map, whereas only four selected the 3D bird's eye view map as their favorite. No participant chose the without map assistant condition.

# 4. DISCUSSION

The primary goal of this study was to investigate whether use of either 2D top-down view maps or 3D bird's eye view maps, compared to no assistant, significantly improved learning of multi-level virtual buildings and subsequent development of multi-level cognitive maps. The multi-level cognitive maps were evaluated on several behavioral test measures of cross-level spatial knowledge. As expected, the reliably better performance on the tasks requiring pointing and vertical alignment between floors with visualization assistance, compared to the control condition, provide evidence of the efficacy of these visualization techniques for promoting the development of multilevel cognitive maps. However, no significant differences were found in the pointing and vertical navigation tasks between the two maps (2D top-down view map vs. 3D bird's eye view map), which is inconsistent with previous research regarding the evaluation of the 2D and 3D maps [3, 12]. One possible explanation is that the 3D map used in our research is a true 3D structural rendering rather than a photorealistic representation of the world [12]. In addition, users could learn the 3D internal structure of the buildings from multiple perspectives, which is known to be helpful for understanding the internal structure of the object compared to learning from a fixed bird's eye view [4], in which, the relative direction and distance between targets can be distorted due to 3D perspective cues. Therefore, the performance gaps between 2D and 3D maps described in previous literature were likely narrowed here, as we made full use of the utility of 3D maps, e.g., true 3D structure and by providing multiple perspectives.

Nevertheless, use of 2D maps outperformed 3D maps in the paper-based drilling task, which we consider as the strongest measure of assessing multi-level cognitive map development. The statistics showed that users had significantly better performance in indicating these targets at contiguous landmarks in the 2D top-down view map condition than the 3D bird's eye view map condition. This suggests that the 2D maps are a better visualization method for allowing participants to realize the continuity between floors, which means that of the techniques tested, they most facilitated development of accurate multi-level cognitive maps supporting behaviors that force cross-floor knowledge and inter-floor alignment (e.g., the drilling tasks).

As for the contiguous landmarks vs. non-contiguous landmarks analysis, there were no significant differences in the pointing and vertical navigation tasks, but there was a significant difference in the paper-based drilling task. We argue that contiguous landmarks are potentially helpful for facilitating multi-level cognitive map development, as they consolidate the individual/local floor-level knowledge into a consistent/global building-level spatial frame of reference. They act similarly to a window in your office that provides visual access to the adjacent library building, which would undoubtedly facilitate your cognitive map development between these spaces, e.g. increased pointing accuracy between your office and the library. However, in this study, users received map assistance in the learning phase only and we did not explicitly highlight any contiguous landmarks on either the 2D maps or 3D maps. Users were not informed of any clues about the contiguous landmark information before beginning the experiment. Despite this lack of explicit knowledge, some participants still perceived and made use of these contiguous landmarks for between floor wayfinding, which supports the importance of visualization techniques that highlight and emphasize these cues. Therefore, in the future, we will further investigate whether explicitly highlighting the contiguous landmarks on the maps improve learning of multi-level buildings and subsequent development of multi-level cognitive maps.

We acknowledge that the error and accuracy performance observed in this study are lower than expected even when assisted with the maps for visualization. There are two reasons that likely account for this outcome. First, the virtual buildings used in this study have much higher structural complexity for transition between floors than the environments used in previous research [15]. The virtual buildings used in our study had incongruent floor layouts and disorienting staircases that consisted of both horizontal and angular offsets between the floors. Furthermore, the virtual buildings were designed with very low architectural differentiation, which was discussed as another main cause of getting lost in indoor spaces [1]. Second, the cross-level tasks used in this study, e.g., vertical navigation and drilling, are inherently more difficult than the frequently discussed "A to B" route navigation tasks, because in our tasks, participants have to vertically align positions on different floors that were never explicitly specified as targets or routes in the learning phase. Therefore, even though participants may have travelled the route between locations in the learning phase, there was no reason to code the vertically-aligned positions in memory. On the other hand, even in such a complex indoor environment and with such difficult tasks, participants showed reliably better performance in the two map conditions than the without map assistant control condition, meaning that the proposed visualization methods are efficient tools in facilitating multi-level cognitive map development.

In this study, most participants indicated that they preferred the 2D top-down view maps to 3D bird's eye maps. Some examples of the positive comments include: "the 2D map made the locations easier to see or point out", "2D map is easier to get a sense of the floor layouts in relation to each other. The 3D map was hard to read and learn", "2D map gives me a better idea of vertical navigation and relation of objects". The preference is not surprising; 2D maps have been used for hundreds, if not thousands, of years and metro maps, which are very similar to the 2D top-down view maps in this study, are products of decades of research and development.

Taken together, the preliminary results from this study show that improved visualization through the use of digital interactive maps aids learning and representation of multi-level buildings. Although performance with the two maps was similar, the 2D top-down view map is considered to be the best visualization approach for developing multi-level cognitive maps as it performed statistically best in the paper-based drilling task, which we argue as the purist measure of cross-floor spatial knowledge. This paper only reports on the preliminary results pertaining to performance accuracy. In the future, more data analyses, e.g., navigation efficiency, vertical navigation centroid analysis, etc., will be run to more robustly evaluate whether the 2D top-down view map is the optimal visual interface for assisting multi-level cognitive map development. In addition, we will analyze users' trajectory data to investigate where users got lost and the nature of the errors that were generated. These data analyses will provide further evidence in answering research questions about when errors occur, e.g., where are distortions between the floor layouts and the formed multi-level cognitive maps? What is the underlying mechanism of integrating separate floor layouts into a consolidated multi-level cognitive map, with or without a map assistant? Is the constructed multi-level cognitive map correlated to the types of cross-level tasks? For example, if participants were asked to make a straight line from the outside to a target inside the building, whether users still perform better in the 2D top-down view map than in the 3D bird's eye view map?

## 5. ACKNOWLEDGMENTS

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