Spatial Cognition & Computation
An Interdisciplinary Journal

ISSN: 1387-5868 (Print) 1542-7633 (Online) Journal homepage: http://www.tandfonline.com/loi/hscc20

Assessment of between-floor structural and topological properties on cognitive map development in multilevel built environments

Hengshan Li & Nicholas A. Giudice

SPATIAL COGNITION & COMPUTATION
2018, VOL. 18, NO. 3, 138–172
https://doi.org/10.1080/13875868.2017.1384829

Assessment of between-floor structural and topological properties on cognitive map development in multilevel built environments

Hengshan Li[a] and Nicholas A. Giudice[b,c]

[a]ETH Zurich, Future Cities Laboratory, Singapore-ETH Centre, Singapore; [b]Spatial Informatics Program: School of Computing and Information Science, University of Maine, Orono, ME, USA; [c]The Virtual Environment and Multimodal Interaction (VEMI) Laboratory, Orono, ME, USA

ABSTRACT

The present study investigated cognitive map development in multilevel built environments. Three experiments were conducted in complex virtual buildings to examine the effects of five between-floor structural factors that may impede the accuracy of humans' ability to build multilevel cognitive maps. Results from Experiments 1 and 2 (of three experiments) revealed that difficulties in developing multilevel cognitive maps are not solely caused by the *z*-axis offset, as is suggested in the literature, but are due to the factorial combination of a between-floor overlap and a *z*-axis offset. Results from Experiment 2 showed that this process becomes substantially more difficult when the reference directions between different floors have an angular offset from each other. Finally, results from Experiment 3 demonstrated that confusing between-floor heading shifts in aligned buildings did not make it reliably harder to build multilevel cognitive maps. The implications of these findings are discussed in terms of theories of mental representations in multilayered three-dimensional spaces, as well as for architectural design.

KEYWORDS
multilevel cognitive maps; multilevel indoor spatial behaviors; multilevel structural and topological properties; cross-level spatial knowledge integration

1. Introduction

Public buildings such as hospitals, shopping malls, airports, etc., are increasingly complex, incorporating incongruent floor layouts, partially overlapped layers, and confusing staircases, all of which can cause people to become disoriented or lost when navigating inside buildings, especially during vertical travel (Carlson, Hölscher, Shipley & Dalton, 2010; Hölscher, Meilinger, Vrachliotis, Brösamle & Knauff, 2006). It is widely accepted that to efficiently reach a destination beyond what is perceptible from one's immediate environment without becoming lost, navigators rely on the support of cognitive maps—an enduring, observer-free spatial representation of the environment (O'Keefe & Nadel, 1978; Tolman, 1948).

CONTACT Hengshan Li li@arch.ethz.ch ETH Zurich, Future Cities Laboratory, Singapore-ETH Centre, CREATE Tower, Singapore, 138602.

Color versions of one or more of the figures in the article can be found online at www.tandfonline.com/hscc.

Similarly, to accurately and efficiently find destinations located on different floors in a complex building, people must form a globally coherent mental representation of the multilevel built environment, which has been termed a multilevel cognitive map (Li & Giudice, 2012). Previous literature has found that integration of spatial knowledge learned from different floors into a globally coherent mental representation is a challenging and error prone spatio-cognitive task for humans (Carlson et al., 2010; Giudice & Li, 2012; Hölscher et al., 2006; Li & Giudice, 2013a; Montello & Pick, 1993; Passini, 1992).

For instance, navigators have been shown to be significantly less accurate when pointing to locations between floors than within a single floor (Giudice & Li, 2012; Li & Giudice, 2013a; Street, 2012). However, there is a surprising dearth of research in the spatial cognition literature addressing the underlying theory of why integrating multilevel building information into a multilevel cognitive map is so challenging for humans. To address this gap, the goal of the current research is twofold. First, we propose a theoretical framework for the development of multilevel cognitive maps during indoor navigation. Second, we investigate how environmental structure and topological properties impact users' development of multilevel cognitive maps based on the proposed framework.

The findings of the current research not only have important ecological validity for better understanding why people get lost inside multilevel buildings, they also provide new basic insights for cognitive mapping theory characterizing how humans mentally represent three-dimensional (3D) space. Jeffery, Jovalekic, Verriotis, and Hayman (2013) reviewed previous literature regarding navigation and mental representation in 3D space and suggested a bicoded representational structure in which space in the plane of locomotion is represented differently from space in the orthogonal axis. On the basis of their synthesis of the extant literature, Jeffery et al. (2013) proposed that "the mammalian spatial representation in surface-traveling animals comprises a mosaic of these locally planar bicoded map fragments rather than a fully integrated volumetric map."

There has been a lively debate in the literature concerning the efficacy of this bicoded representation (Hölscher, Büchner, & Strube, 2013; Klatzky & Giudice, 2013; Schultheis & Barkowsky, 2013; Wang & Street, 2013). For instance, Schultheis and Barkowsky (2013) argued that the lack of empirical evidence supporting a 3D volumetric representation in the brain of surface-travelling animals is more indicative of the necessity rather than the ability to maintain such representational structures, as for many spatial tasks the vertical information is either irrelevant to the task or partly redundant with horizontal information. In addition, Yartsev and Ulanovsky (2013) found evidence that the hippocampus can represent 3D space by a uniform and nearly isotropic rate code along three axes, as with Egyptian fruit bats.

However, no neurological evidence for such 3D representations has been observed in humans. Although little is known about whether humans are born with the capacity to construct true 3D spatial representations in the brain, researchers on both sides of this debate agree that more empirical studies should be conducted to investigate how humans integrate 3D spatial knowledge in real and virtual settings (Jeffery et al., 2013; Yartsev & Ulanovsky, 2013). The current research aims to shed new light on this fundamental issue by studying how between-level structural and topological properties affect users' development of multilevel cognitive maps.

Before we describe the specifics of these properties, we first introduce the framework of multilevel cognitive map development, which plays an important role in understanding how people integrate cross-level spatial knowledge. It also provides an important foundation for why we chose the specific between-level properties we studied in the current research.

2. A framework for multilevel cognitive map development

To build a cognitive map of a new environment, people usually acquire spatial knowledge by exploring and learning surrounding space (Downs & Stea, 1973). Similarly, to develop a multilevel cognitive map of a new building, navigators have to explore and learn the constituent layers, maintain their orientation during vertical transitions, and update their heading after vertical travel. We argue that a fundamental component (and frequent bottle neck) of learning multilevel built environments is considering what happens when navigators use vertical connectors (e.g., elevators, staircases, escalators) to travel between floors. An important concept relating to this vertical travel process is "transition points," defined as the point where users pass through a between-floor portal, such as an elevator door to enter or exit a floor by a vertical connector (Li & Giudice, 2012). A transition point has a direction and a location component based on the orientation and location of a between-floor portal.

Another important concept for navigation is 'reference direction', referring to the orientation of a spatial reference system or a spatial reference frame (McNamara, Sluzenski, & Rump, 2008; Wang, 2012). In indoor spaces, a reference direction often refers to the orientation of a local reference frame, such as a room or a floor. The orientation of this local reference frame is generally defined by several factors, including the navigator's initial experience with the space (e.g., after entering a floor), the primary orientation experienced within the space, and its overall structure (e.g., the principle axes of a room or a building) (Kelly & McNamara, 2008; McNamara et al., 2008; Meilinger, Riecke, & Bülthoff, 2013; O'Keefe, 1991).

Given that we focus on between-floor spatial knowledge integration in this article, and for simplicity, we assume that a navigator's velocity vector (course) and facing direction (heading) are the same as the transition point's direction when entering or exiting a between-floor portal. Course and heading are the direction of a navigator's velocity vector and facing direction, respectively, measured with respect to a reference direction (Gallistel, 1990; Loomis, Klatzky et al., 1999).

When people navigate between floors, they must travel through a pair of transition points. For example, as shown in Figure 1 (a), there is one pair of transition points ($p1$ and $p2$) connecting Floor 1 and Floor 2. Navigation between the two floors involves a vertical transition offset (h), a horizontal transition offset (l), and a transition angular offset (α) (Li & Giudice, 2012). The vertical transition offset is the z-axis offset between this pair of transition points located on different floors. The horizontal transition offset is the offset between the transition point ($p1$) and the projection of the corresponding transition point ($p2'$) on the former transition point's floor (e.g., floor 1). The transition angular offset is the difference between the navigators' facing direction at a pair of transition points (Li & Giudice, 2012).

On the basis of defined terms, in this article the transition angular offset is defined as the between-floor heading shift (denoted by α). The angular offset between the reference direction of a floor and a navigator's heading when entering or exiting a between-floor portal is defined as the portal-floor heading shift, denoted as $\beta 1$ and $\beta 2$ respectively on two floors, as shown in Figure 1 (b).

Additionally, previous literature has defined the movement from one reference frame to the next as a perspective shift, which consists of both a translation and a rotation component (Meilinger, 2008; Meilinger et al., 2013). In this article, the rotational component of the perspective shift is denoted by γ. The translational component of the perspective shift involves

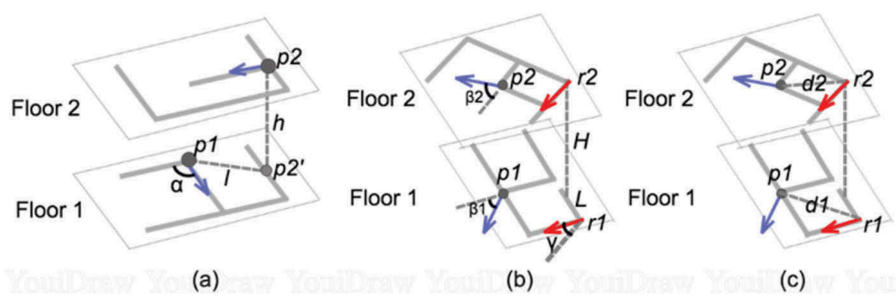

Figure 1. (a) Transition points in multilevel built environments. The blue arrows indicate the directions of a pair of transition points (p1 and p2), which are not coincident, meaning that during vertical travel there will be a horizontal offset l. A pair of transition points can be connected via a staircase, an elevator, or an escalator. When two transition points are connected by an escalator, there will be both vertical and horizontal transition offsets. (b) Portal-floor heading shifts ($\beta 1$ and $\beta 2$) on two floors. The red arrows indicate the reference directions of the two floors. (c) Transition reference offsets ($d1$ and $d2$) on two floors.

both a horizontal perspective offset (L) and a vertical perspective offset (H), as illustrated in Figure 1 (b). For simplicity here, we assume that no horizontal perspective offset is involved in between-floor transitions, meaning that between-floor reference points (denoted as $r1$ and $r2$) are always vertically aligned for the current article.

The horizontal offset between a floor's transition point and reference point is defined as the *transition reference offset*, denoted as $d1$ and $d2$, respectively, on separate floors, as illustrated in Figure 1 (c). For simplicity here, it is assumed that the transition reference offset equals zero degrees on each floor, meaning that the transition point and the reference point are overlapped ($d1 = 0$, and $d2 = 0$).

Navigators usually do not have direct perception of both floors during vertical transition due to occlusion from elevator shafts or stairwells. Instead, they have to sense rotary accelerations, based on kinesthetic, vestibular, or optic cues, and "doubly integrate this information to obtain rotational displacements" (Loomis, Klatzky et al., 1999). This process is termed path integration, referring to the updating of position and heading on the basis of velocity and acceleration information (Loomis, Klatzky et al., 1999; Loomis et al., 1993). It is worth noting that during vertical transition, navigators still have direct perception through visual and other sensing of their immediate surroundings, such as the space within an elevator. This perceived information may provide important cues about the between-floor heading shift. However, during vertical transition the portal-floor heading shift is often not directly perceivable, unless the elevators and floors are transparent. When a multilevel building has no between-floor visual access, as is most commonly the case, navigators must depend on the between-floor heading shift (α) and the two portal-floor heading shifts $\beta 1$ and $\beta 2$ in order to integrate cross-level spatial knowledge. Thus, we argue that path integration plays an important role in supporting the integration of cross-level spatial knowledge during the requisite vertical transition associated with navigating between floors.

For a given between-floor perspective shift γ, there are 12 different situations where path integration of cross-level spatial knowledge occurs (see Appendix Figure A1 for more details). If the transition reference offsets ($d1$ and $d2$), the horizontal transition offset (l), and the horizontal perspective offset (L) are all taken into consideration for the integration of cross-level spatial knowledge, the process of path integration will become more complex. Previous literature has found that increasing path complexity in terms of the number of turns and overall route length increases the difficulty of path integration (Etienne & Jeffery, 2004; Klatzky, Beall, & Loomis, 1999; Loomis, Klatzky, et al., 1999; Loomis et al. 1993). It is not surprising that integrating multilevel building information into a multilevel cognitive map is cognitively challenging for human navigators.

Based on the framework illustrated here, we define multilevel cognitive maps here as consisting of:

(1) A set of single-level cognitive maps. From a mathematical perspective, a single-level cognitive map is a surface (i.e., two-dimensional boundary that can be flat or curved). The projections of these single-level cognitive maps in the vertical dimension are super-imposed.
(2) Between-floor connectivity information (i.e., a finite collection of paired transition points between a transition point $\overrightarrow{t_i}$ on floor A and a transition point $\overrightarrow{t_j}$ on floor B). In this article a transition point is defined as a vector, as the process of between-floor transition involves both position (where a navigator enters a new floor) and direction (which direction a navigator is facing upon entering the new floor).
(3) Between-floor alignment information (i.e., a finite collection of paired places between a place p_i on floor A and the vertical projection of p_i on floor B, denoted as p_i'). As illustrated in Figure 2, navigators could calculate between-floor alignment information based on the perspective shift γ. Between-floor alignment information involves no directional information, and thereby is not represented as a vector.
(4) Encoding of the *z*-axis. Previous literature has shown that humans can roughly estimate distance between floors, although the estimations are

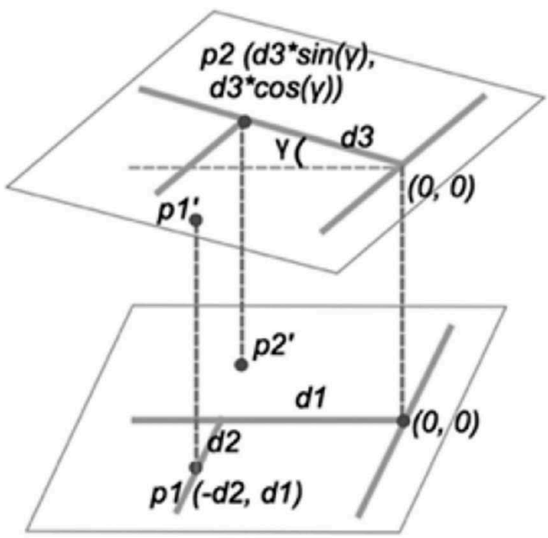

Figure 2. Calculating between-floor alignment information based on the perspective shift γ and a pair of transition points. It is assumed here that there is no horizontal transition offset between the two transition points.

distorted, with "relative downward errors in upward judgments and relative upward errors in downward judgments" (Jeffery et al., 2013; Tlauka, Wilson, Adams, Souter, & Young, 2007; Wilson, Foreman, Stanton, & Duffy, 2004). However, investigating the encoding and distortion of the *z*-axis dimension goes beyond the scope of the current research.

3. Environmental factors influencing multilevel cognitive map development

The current research identifies and examines five between-level structural and topological properties. These properties were chosen as we believe they most influence users' development of multilevel cognitive maps, as shown in Figure 3 and Figure 4.

(1) *Z-axis offset*. A multilevel building contains multiple floors, and each floor has a z-axis value (e.g., floor height), meaning that different floors are separated by a *z-axis offset* (i.e., vertical distance between floors), as shown in Figure 3(b). The z-axis offset usually equals the vertical transition offset (h) or the vertical perspective offset (H).

(2) *Between-floor overlap*. Two floors of a building can be displaced so as to be nonoverlapped between floors, as in Figure 3(b), or to be overlapped between floors, as in Figure 3(c). This factor can be thought of as a continuum from no overlap (0%) to completely overlapped (100%), if two floors are matched at their boundaries. When two floors of a building are overlapped, there must be a set of positions within the two floors colocated at the same *x-y* coordinates. Between-floor partially and fully overlapped floors are both considered as encompassing the *between-floor overlap* factor. For simplicity in the current article, however, we focus on fully overlapped floors.

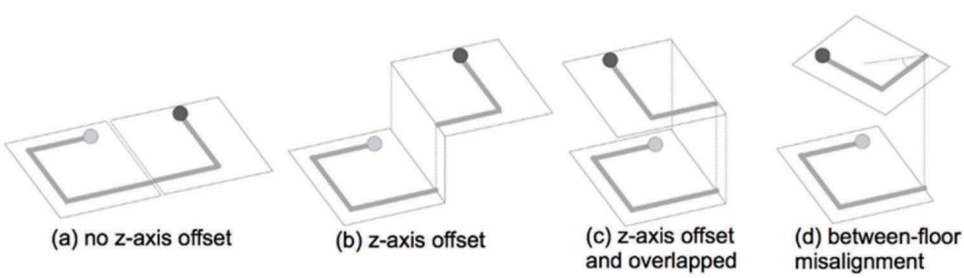

Figure 3. These figures depict the *z*-axis offset, between-floor overlap, and between-floor misalignment.

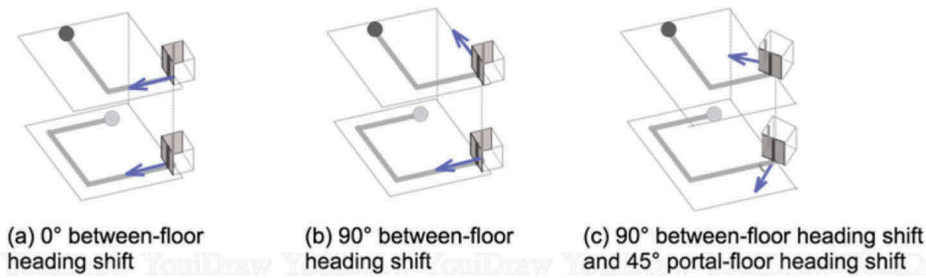

Figure 4. These figures depict the 90° between-floor heading shift and 45° portal-floor angular offset. (a) (b) (c) (d)

(3) *Between-floor misalignment*. If two floors' reference directions have a perspective shift, the two floors can be said to be misaligned, as shown in Figure 3(d).
(4) *Between-floor heading shift*. As depicted in Figure 4(b), the elevator has separate entrance and exit doors that are offset by 90°, meaning that navigators will experience a 90° between-floor heading shift after vertical travel.
(5) *Portal-floor heading shift*. As shown in Figure 4(c), navigators will experience not only a 90° between-floor heading shift after vertical travel but also a 45° portal-floor heading shift before entering and after exiting the elevator.

The goal of this article is to investigate which of the above-mentioned multilevel structural factor(s) can best account for confusion of learning multilevel buildings and best explain the errors observed for between floor behaviors, as identified from previous literature. We conducted three experiments using desktop virtual environments (desktop VEs), as described in the following sections, to examine the effects of these five multilevel structural and topological properties (or the combination of these factors) on human mental representation of multilevel built environments.

3.1. *Experiment 1*

In Experiment 1, we investigate two principle factors including the z-axis offset and the 90° between-floor (or between-region) heading shift that may contribute to challenges in multilevel cognitive map development. The first research question addressed by Experiment 1 asks: is the *z*-axis offset solely attributable to impairment in the development of multilevel cognitive maps?

Previous literature has found clear empirical evidence that humans can encode elevation and the z-axis offset in both outdoor and indoor spaces, even if not in a precise 3D manner (Garling, Böök, Lindberg & Arce, 1990;

Hayman, Verriotis, Jovalekic, Fenton & Jeffery, 2011; Tlauka et al., 2007). However, the previous literature regarding the effect of the z-axis offset on navigators' between-floor behaviors such as pointing and wayfinding is also somewhat contradictory. For instance, Montello and Pick (1993) conducted a study in and around a university building. Participants learned two distinct routes located on different floors that never crossed. After walking the two routes, participants were told how these two routes connected. In the pointing task, participants were more accurate at pointing to locations within the route they were presently on than locations on the other route. This result provides compelling evidence that (1) it is difficult to build a globally coherent mental representation of a multilevel building, and (2) between-route pointing (i.e., between-floor) is more error-prone than pointing within a route. One route used in their study contained two sections with one section inside the building and the other outside. The outside section was one floor above the inside section (i.e., the two sections had a different *z*-axis offset). Surprisingly, the results showed that between-section pointing accuracy was comparable to within-section pointing, suggesting that the *z*-axis offset did not necessarily affect users' pointing performance. This finding was influential on motivating the current research.

Recent studies have also shown that navigators are significantly less accurate when pointing to locations between floors than within a single floor (Giudice & Li, 2012; Li & Giudice, 2013a). However, the within- and between-floor routes used in these studies differed in complexity from each other in terms of the number of turns and overall route length. This is an important factor to control as previous literature has found that the longer the travelled route, the larger the path integration error (Etienne & Jeffery, 2004; Klatzky, Loomis, & Golledge, 1997; Loomis et al., 1993; Wan, Wang, & Crowell, 2013). Thus, the relative pointing performance of between- and within- floor judgments in the previous studies are difficult to interpret, as the observed between-floor effect might be due to the need of encoding and representing longer between-floor routes rather than the z-axis offset.

To study the effect of the z-axis offset in isolation, the current study used two single-floor buildings with two regions, pictured in Figure 5 (a) and (b), which were compared with two two-floor buildings, shown in Figure 5 (c) and (d). A *region* represents an encoded representation in spatial memory in which perceived locations are grouped within a common spatial reference frame (Wiener & Mallot, 2003). The two regions of the single-floor buildings were connected by an "elevator," which supported users' horizontal transition between the two regions on the same plane, instead of vertical up/down transitions between floors. The two regions of the single-level buildings and the two floors of the multilevel building (including a *z*-axis offset) were matched for layout complexity. With this design, we were able to isolate and examine the effect of the *z*-axis offset on users' development of multilevel

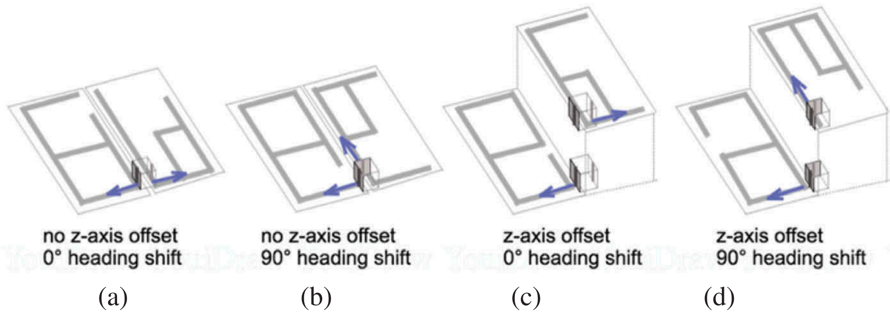

Figure 5. Floor layouts of Experiment 1 from a bird's eye view. Buildings 1 and 2 had only one floor with two nonoverlapped regions (no *z*-axis offset), whereas buildings 3 and 4 had two nonoverlapped floors (but with a *z*-axis offset). Buildings 1 and 3 had an elevator with a 0° heading shift, whereas buildings 2 and 4 had an elevator with a 90° heading shift.

cognitive maps by comparing their performance on cross-level spatial behaviors across the four building layouts.

The second research question addressed by Experiment 1 asks: does the 90° heading shift during between-floor (or between-region) transition impair the development of multilevel cognitive maps? According to the proposed framework of multilevel cognitive map development, the between-floor heading shift (α) is an important component for navigators to integrate between-floor spatial knowledge during vertical travel. Previous literature has found that confusing staircases are one of the main reasons for becoming lost inside buildings (Carlson et al., 2010; Hölscher et al., 2006). However, two factors are involved in vertical transitions via a staircase: the between-floor heading shift and additional movements and turns in the stairwell that must be updated in order to maintain accurate orientation. Thus, it is unclear whether the difficulty of using staircases for vertical transition asserted in the previous literature was caused by the between-floor heading shift or by errors in updating these additional movements and turns imposed by navigating the stairwell. To address this issue in Experiment 1, navigators only used elevators for vertical transitions, as this between-floor mode of transport eliminates any potential confound from the additional rotations imposed by using stairs.

3.1.1. *Method*

Sixteen participants (eight females and eight males, mean age = 20.1, *SD* = 2.0) were recruited from the University of Maine student body.

The experimental environments were displayed on a Samsung 43" Class Plasma HDTV monitor running at 60 Hz at a resolution of 1024 × 768, as shown in Figure 6. We ran the desktop VEs using a Lenovo W510 Thinkpad 15.6-inch workstation notebook (Intel Core i7 processor and NVIDIA Quadro FX 880M graphics). We used the Unity VR engine 4.3 (Unity

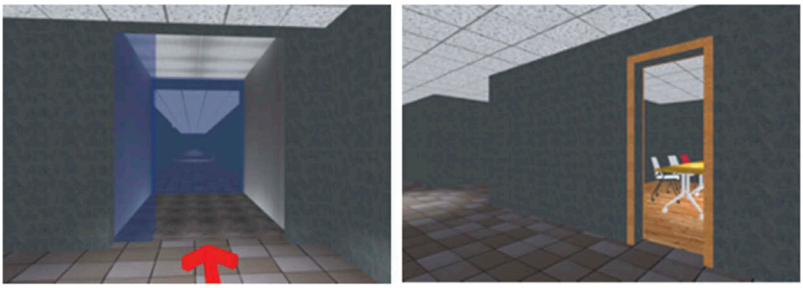

Figure 6. Virtual environments (left panel: An elevator, right panel: A target room).

Technologies) as the VE platform supporting users' real-time navigation and recording their trajectory and test performance. Participants used a Logitech Extreme 3D Pro Joystick to make both translational and rotational movements.

Our environments comprised four nonoverlapped buildings designed using Revit Architecture 2013 (AutoDesk, Inc.). The four buildings were matched for layout complexity but had distinctive between-floor topological and structural properties (i.e., the z-axis offset and between-floor heading shift), as pictured in Figure 5.

As illustrated in Figure 7, each building contained four rooms: a bathroom, a classroom, a conference room, and an office, serving as targets. The four rooms had the same size (5m × 5m) but distinctive interior objects and floor textures. The locations of the four rooms were balanced among the four buildings.

We acknowledge that multilevel buildings are generally large structures with many rooms of different sizes and configurations. Although the current design sacrifices some level of ecological validity, the advantage of our approach is that we could control the available information participants could use for self-orientation and wayfinding, which we believe is most important for addressing our variables of interest.

Each building contained a single elevator, whose design could take one of two forms, one including a between-floor (or between-region) heading shift and the other without this heading shift, as shown in Figure 5. The entrances

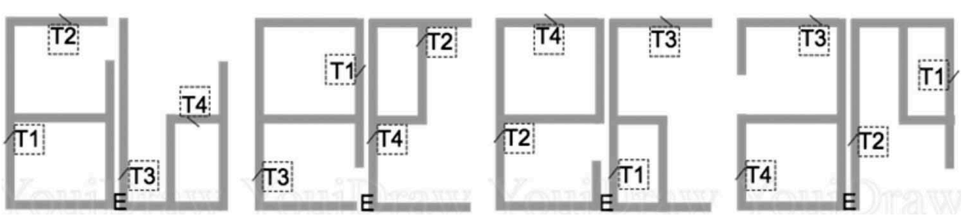

Figure 7. Floor layouts of Experiment 1 from a top-down view. 'E' represents the elevator. 'T1' to 'T4', respectively, represent the classroom, conference room, office, and bathroom.

of elevators were semitransparent, so users received continuous visual cues indicating vertical displacement during between-floor travel. In addition, the experimenter verbally provided participants with the floor number as soon as the elevator arrived at that floor (e.g., "you are now arriving at floor 2"). There was no vertical optic flow information for the between-region single-level conditions, as the elevator did not 'move' in these conditions. Participants remained within the elevator for the same amount of time (5 seconds) during both vertical and horizontal transitions. The overall route length and the number of turns for within-floor routes were matched for each building, as illustrated in Figure 8. The number of turns during vertical travel, however, differed according to how the two floors or regions are connected, as shown in Appendix Figure A1.

A within-subject design was adopted, with the 16 participants running in all four conditions. Each building layout was used in a pseudorandom fashion, ensuring that the effects of floor layout as well as the outbound learning route on users' development of cognitive maps was well balanced.

3.1.2. *Procedure*

All participants in Experiments 1–3 followed the same procedure.

Phase 1: *Practice*. Participants were familiarized with the apparatus and navigation behavior in the VE. All experimental tasks were explained and demonstrated before starting the experimental trials.

Phase 2: *Learning*. At the beginning of the experiment, participants were situated at one position facing the elevator. A red arrow on the ground indicated north. Participants were asked to turn in place and to use what they could see of the environment (e.g., the building's layout, the north arrow, the elevator) to orient themselves. Participants were then guided by blue arrows on the ground to traverse a route that exposed all of the target rooms during travel. These arrows disappeared in the testing phase. The predetermined route was not necessarily the shortest path through the building. Instead, the route was designed to maximize floor coverage and building exposure in order to facilitate learning of the entire space. The elevator had separate entrance and exit doors. After participants entered

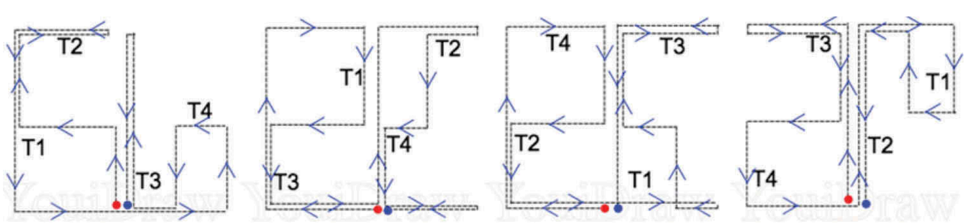

Figure 8. Learning routes of the four buildings. The red dot represents the start point, and the blue dot represents the end point.

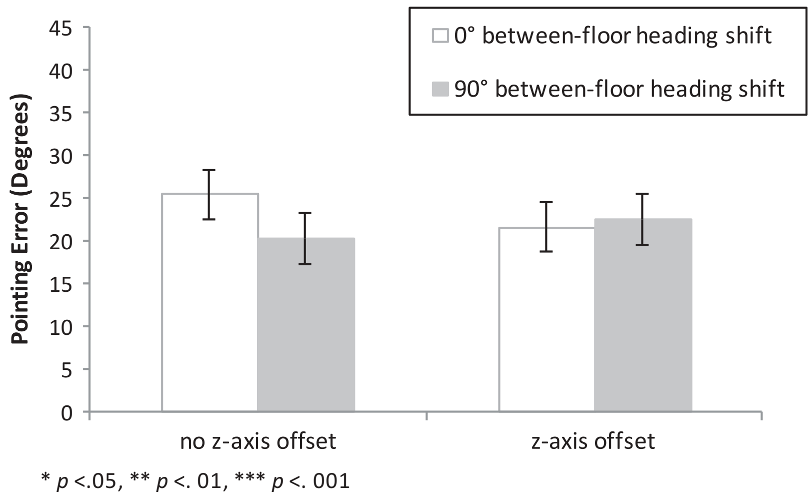

Figure 9. Mean absolute pointing errors for Experiment 1.

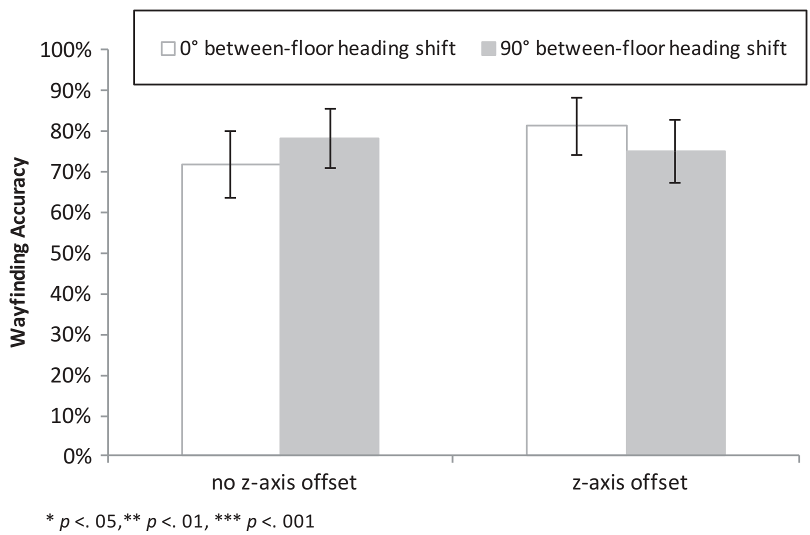

Figure 10. Mean absolute wayfinding accuracy for Experiment 1.

the elevator, they were asked to make a turn to face the elevator exit. There were no additional movements and turns when using the elevator for vertical and horizontal transitions.

Phase 3: *Pointing criterion task*. This task was important to ensure that all participants had reached a common baseline level of learning and had formed accurate single-level cognitive maps before moving on to the testing phase requiring use of between-floor (or between-region) knowledge. For this test, participants were first randomly situated at a previously learned room and a red arrow appeared, indicating north. The experimenter then asked them to become oriented at this location, using any information they could avail themselves of by looking around the surrounding environment. When participants were ready, the experimenter asked them to turn to face a straight line to the elevator on the current floor as quickly as possible without compromising accuracy. In other words, we did not want a speed accuracy trade-off and wanted participants to know that we were measuring both their accuracy in performing the task as well as their speed to do so. The elevator was never within sight during this task. To perform the task, participants rotated in the VEs by twisting the joystick and when they believed they were facing toward the elevator, they pulled the trigger to log their response. A red crosshair on the screen indicated participants' facing direction. To meet the criterion, they needed to point to the elevator within an error tolerance of 20°. If they failed the first iteration, the Phase 2 learning and Phase 3 pointing criterion tests proceeded until they either successfully met criterion or made five incorrect attempts. Approximately 10% of the total participants across Experiments 1–3 failed to pass the criterion task after exhausting the 5 retraining sessions, partly due to experiencing motion sickness. These participants were subsequently replaced.

Phase 4: *Inter-target pointing task*. Participants were first randomly positioned at the doorway of one of the target rooms. They were encouraged to self-orient, as was done in Phase 3. The experimenter then gave them the name of a second target located on a different floor (or region) and asked them to turn to face a straight line to that room. If the target room was on a different floor, they were instructed to ignore the vertical dimension and to point as if the target was on the same plane as their current floor. They pulled the joystick's trigger when they felt they were properly oriented so as to indicate a straight line to the requested target. Two dependent variables for the pointing task were analyzed: pointing latency and absolute pointing error.

Phase 5: *Wayfinding task*. Participants were first randomly positioned at the doorway of a target room. They were encouraged to orient themselves as they did in Phase 3. The experimenter then gave them a second target name and required participants to navigate to the target (between-floor or between-region on the same floor) using the shortest possible route. All room doors were closed, and the room names were no longer present, so participants had to find the target room based on the support of their formed multilevel cognitive maps. Upon reaching the perceived location of the target, they turned to face it and pulled the joystick's trigger. If they were correct, the target room appeared. If incorrect, they were guided to the correct location before proceeding to the next trial. Two dependent variables were analyzed for this task: wayfinding accuracy (whether participants indicated the correct location and orientation of the target room) and wayfinding efficiency (shortest route length over traveled route length).

3.1.3. *Results and discussion*

The means and standard errors for all dependent measures, separated by *z*-axis offset and between-floor heading shift for Experiment 1, are provided in Appendix Table B1. A 2 (z-axis: no offset vs. offset) × 2 (between-floor or between-region heading shift: 0° vs. 90°) repeated-measures ANOVA was conducted for each of the four dependent measures (absolute pointing error, pointing latency, wayfinding accuracy, and wayfinding efficiency). As shown in Figure 9 and Figure 10, there was no significant main effect of the z-axis offset for any measure: absolute pointing error, $F(1, 15) = 0.086$, $p > .05$, $\eta^2 = .006$; pointing latency, $F(1, 15) = .346$, $p > .05$, $\eta^2 = .023$; wayfinding accuracy, $F(1, 15) = 0.238$, $p > .05$, $\eta^2 = .016$; or wayfinding efficiency, $F(1, 15) = 0.175$, $p > .05$, $\eta^2 = .012$.

In this study the between- and within-floor routes had exactly the same number of decision points (e.g., turns) and an equivalent route length. Therefore, if the z-axis factor led to difficulty in cross-level spatial knowledge integration, participants would exhibit greater errors when pointing or wayfinding to targets located on different floors than when they were on the same floor. However, no such effect of the z-axis offset was observed for any measure.

Based on the observed effect sizes, we used G*power to determine how many subjects would have been necessary for statistical significance at a power level of .95. We found that detection of reliable differences of pointing error was unlikely unless our sample size was dramatically increased ($n > 20{,}000$), meaning that we have an extremely low possibility of making a Type II error when accepting our results as supporting the null hypothesis.

Tying back to the initial research question of whether the z-axis offset can solely be attributed as impairing the development of multilevel cognitive maps, the results from Experiment 1 revealed that the z-axis offset alone is not the root of this problem. The implication of this finding is that some multilevel buildings such as stadiums and terrace-like architectures, although comprising multilevel structures, are not necessarily more challenging to learn and to navigate than their single-level counterparts. Although the effect of the *z*-axis offset was not observed in Experiment 1, it does not rule out an effect of this factor. It simply indicates that the *z*-axis offset alone is not the sole determinant of the problem.

Previous literature has found that the presence of a z-axis offset impairs the development of multilevel cognitive maps (Giudice & Li, 2012; Li & Giudice, 2013a). Based on the results of this study, we postulated that the between-floor effects found in the aforementioned studies were caused by the combination of a between-floor overlap factor and a z-axis offset factor, rather than the z-axis offset alone. This assertion was tested and validated in Experiment 2.

With respect to our second factor of interest, we found no significant main effect of the 90° between-floor (or between-region) heading shift for any measure: absolute pointing error, $F(1, 15) = .391$, $p > .05$, $\eta^2 = .025$, pointing latency, $F(1, 15) = .115$, $p > .05$, $\eta^2 = .008$, wayfinding accuracy, $F(1, 15) = 0.0001$, $p > .05$, $\eta^2 = .0001$, or wayfinding efficiency, $F(1, 15) = 0.001$, $p > .05$, $\eta^2 = .0001$. These results suggest that the 90° between-floor (or between-region) heading shift also did not impair users' development of multilevel cognitive maps, at least not in any of the buildings tested in Experiment 1.

It is possible that our lack of an effect could have been due to our building design; that is, all of the Experiment 1 buildings were nonoverlapped but shared the same reference direction, meaning that participants might have used this spatial regularity as an orienting cue. For instance, in the learning phase of Experiment 1, navigators learned the building by executing two guided tours and then took part in a criterion pointing task to ensure that they had built accurate single-level survey knowledge from this process. During these two phases, navigators might have deduced that the two floors of the buildings were aligned and shared a common spatial reference. For instance, they could use interior features such as hallways, walls, and even the entrances of elevators to learn the common reference direction between floors to complement their path integration process.

As expected from the null main effects, no interaction effects were found between the factors of z-axis offset and between-floor (or between-region) 90° heading shift for any measures: absolute pointing error, $F(1, 15) = 1.121$, $p > .05$, $\eta^2 = .070$; pointing latency, $F(1, 15) = .108$, $p > .05$, $\eta^2 = .007$; wayfinding accuracy, $F(1, 15) = 0.789$, $p > .05$, $\eta^2 = .050$; or wayfinding efficiency, $F(1, 15) = 0.888$, $p > .05$, $\eta^2 = .056$.

Given the ambiguous Experiment 1 results on between-floor (or between-region) 90° heading shift, Experiment 3 was conducted in order to further explore the effect of a between-floor heading shift on users' development of multilevel cognitive maps. Before we look at this issue, however, we first address the key research question: if not the *z*-axis offset alone, which factor (or combination of factors) leads to the between-floor effect found in the aforementioned studies? This question is taken up in Experiment 2.

3.2. *Experiment 2*

The first research question addressed by Experiment 2 asks: does the factorial combination of a between-floor overlap and the z-axis offset impair the development of multilevel cognitive maps? In Experiment 1, we found that the z-axis offset cannot be solely attributable to the difficulty of integrating cross-level spatial knowledge.

In a study on indoor navigation by Street (2012), two groups of participants learned a multilevel campus building. One group used an elevator to navigate between floors, and the other group used a staircase for vertical transition. After learning the building, both groups were asked to point to within-floor and between-floor targets (with the same route length). The results showed that the overall pointing error for the group using the elevator was significantly less than of the group using the staircase. This result suggests that any additional movements and turns imposed by use of the stairs for between-floor transitions cannot be the sole source of the difficulty observed in between-floor pointing performance.

Additionally, for the elevator group, navigators still exhibited larger between-floor pointing errors than in the within-floor pointing trials, even though the within- and between-floor routes had the same level of complexity in terms of turns and route lengths. Street (2012) did not propose what factor might lead to this between-floor effect. However, on the basis of our Experiment 1 results and the framework of multilevel cognitive maps proposed here, we postulate that the between-floor effects found in the literature were caused by the combination of the between-floor overlap and the *z*-axis offset factors rather than the z-axis offset alone.

The multilevel buildings used in the aforementioned experiments consisted of fully overlapped floors, so it is unclear whether the negative effects of between-floor behaviors found in these studies were caused by the z-axis offset, or the between-floor overlap (or a combination thereof that can not easily be disentangled). To address this issue, the current research used a set of "ideal" virtual environments (see the method) to disentangle these factors in order to better understand the between-floor effect, which is an important manifestation of the underlying representation of multilevel buildings.

Previous studies on qualitative spatial reasoning have found that direction relations between points can be implied by the relation of ancestor regions (i.e., regions that the points are located in) (Papadias & Egenhofer, 1997). With respect to multilevel built environments, the implication is that navigators can use the relation of two floors for the directional judgment of two positions located on the two floors. For instance, if two floors (A and B) are nonoverlapped and floor A is located at the north of floor B, navigators can roughly estimate that the direction relations between two positions (*p1* on floor A and *p2* on floor B) could be north, northeast or northwest. However, if two regions are overlapped, there is critical information loss as no conclusion about the direction relation between points can be drawn based on ancestor regions (Papadias & Egenhofer, 1997). Thus, if floor A and floor B are overlapped, the direction relations between *p1* and *p2* could be arbitrary. In this case, when two floors of a building are overlapped, navigators cannot use the two floors' relation (floor A and floor B) to imply the direction of two positions (*p1* and *p2*) located on the two floors. Taken together, we postulated that the between-floor effects found in the aforementioned studies were caused by the combination of the between-floor overlap and the z-axis offset factors rather than the *z*-axis offset alone.

The second research question addressed by Experiment 2 asks: does a 45° between-floor misalignment affect the development of multilevel cognitive maps? Werner and Schindler (2004) studied the effect of misalignment of local reference frames on cognitive map development in a single-floor virtual building. They systematically manipulated the orientation of an elevator, either misaligning its axis or aligning it with respect to the floor's local reference frame. The results showed that participants' pointing accuracy and wayfinding performance was significantly diminished in the misaligned condition (45°) relative to the aligned condition. However, no empirical studies to our knowledge have examined the effect of between-floor misalignment on the integration of cross-level spatial knowledge, as is the focus of the current study.

As discussed in the introduction, the path integration process of integrating cross-level spatial knowledge learned from different floors into a multilevel cognitive map is challenging and error-prone for humans to perform accurately (Carlson et al., 2010; Giudice & Li, 2012; Hölscher et al., 2006; Li & Giudice, 2013a). Previous literature has found that navigators typically assume that the organization of a given floor extends to all floors (Carlson et al., 2010; Hölscher, Brösamle & Vrachliotis, 2012). However, if two floors of a building are misaligned, this assumption is violated. Thus, we predict the same outcome in a multilevel building as was found in the single-level building—the presence of between-floor misalignment would impair the development of multilevel cognitive maps in the current study.

3.2.1. *Method*

Sixteen participants (eight females and eight males, mean age = 21.6, *SD* = 1.8) were recruited from the University of Maine student body (none had participated in Experiment 1). The experimental procedure was the same as Experiment 1, except that the tested environments differed, as illustrated in Figure 11.

The four buildings were systematically manipulated based on two between-floor structural properties (between-floor overlap and misalignment). The two regions of buildings 1 and 2 were matched with the two floors of buildings 3 and 4 in regard to layout complexity. By comparing users' performance between nonoverlapped single-floor buildings (1 and 2) and overlapped two-floor buildings (3 and 4), we can examine the effect of the between-floor overlap (combined with the z-axis factor) on the development of multilevel cognitive maps.

As illustrated in Figure 11, the second region of building 2 and the second floor of building 4 were rotated 45° with respect to the other region or floor of buildings 1 and 3. By comparing users' performance between the two types of buildings (45° perspective shift vs. no perspective shift), we can examine the effect of the floor misalignment on the development of multilevel cognitive maps.

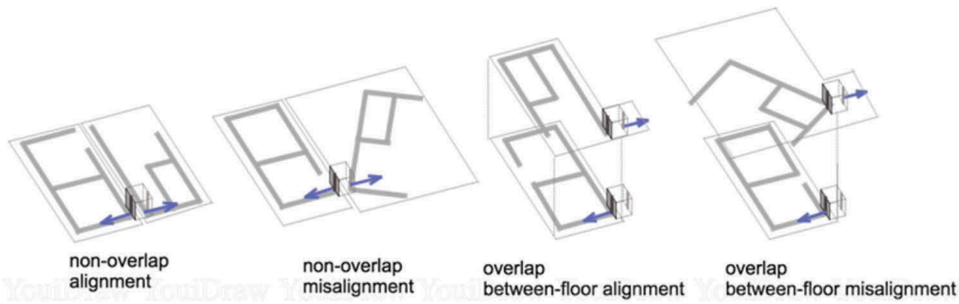

Figure 11. Floor layouts of Experiment 2. Buildings 1 and 2 had a single floor with two regions, whereas buildings 3 and 4 consisted of two overlapped floors. The second region/floor of buildings 2 and 4 were rotated 45° with respect to the first region/floor.

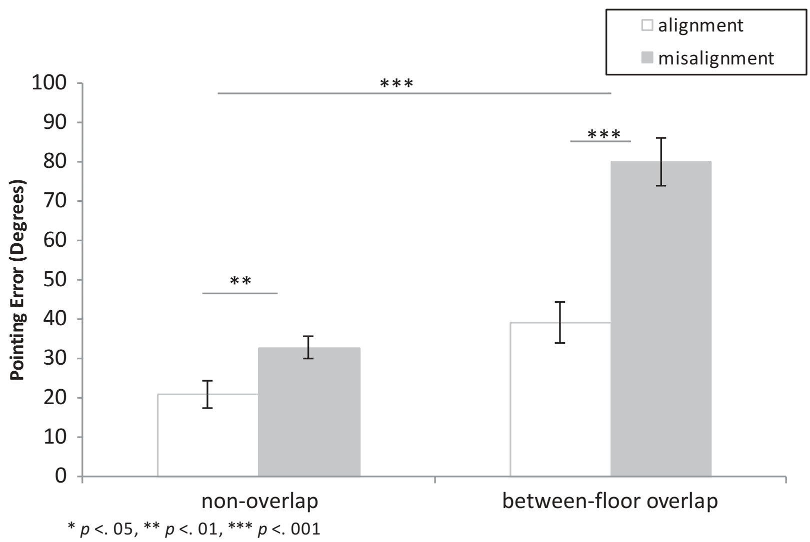

Figure 12. Mean absolute pointing error for Experiment 2.

3.2.2. *Results and discussion*

The means and standard errors for all dependent measures, separated by overlap and alignment for Experiment 2, are provided in Appendix Table B2. A repeated measures ANOVA was run for each of the four dependent measures (absolute pointing error, pointing latency, wayfinding accuracy, and wayfinding efficiency) with two within-subject factors (between-floor overlap and misalignment).

Significant main effects of between-floor overlap were observed for pointing error, with pointing in nonoverlapped buildings being more accurate than in overlapped buildings: pointing error, $F(1, 60) = 66.486$, $p < .0001$, $\eta^2 = .816$. The result suggests that the presence of overlapping floors made it harder for navigators to construct an accurate multilevel cognitive map. No effects of between-floor overlap were observed for pointing latency, $F(1, 15) = 4.272$,

$p > .05$, $\eta^2 = .222$; wayfinding accuracy, $F(1, 15) = .045$, $p > .05$, $\eta^2 = .003$; wayfinding efficiency, $F(1, 15) = .0001$, $p > .05$, $\eta^2 = .0001$.

Significant main effects of misalignment were observed for all measures: pointing error, $F(1, 15) = 42.803$, $p < .0001$, $\eta^2 = .740$; pointing latency, $F(1, 15) = 5.882$, $p < .05$, $\eta^2 = .282$; wayfinding accuracy, $F(1, 15) = 4.765$, $p < .05$, $\eta^2 = .241$; and wayfinding efficiency, $F(1, 15) = 5.649$, $p < .05$, $\eta^2 = .274$. These results demonstrate that participants exhibited greater pointing errors, longer pointing latencies, and lower navigation accuracy and efficiency in misaligned buildings than in aligned buildings. Taken together, these results provide clear evidence that between-floor misalignment represents a substantial factor leading to the challenge of developing accurate multilevel cognitive maps.

As shown in Figure 12, the interaction effect between the factors of misalignment and between-floor overlap was significant for pointing error, $F(1, 15) = 12.535$, $p < .005$, $\eta^2 = .455$. Subsequent Dunn–Sidak pairwise comparisons revealed that the interaction was driven by the between-floor misalignment condition, which took longer and yielded larger errors than the two alignment conditions ($p < .001$). Interaction effects between the two factors of misalignment and between-floor overlap on pointing latency, wayfinding accuracy, and wayfinding efficiency were not observed, pointing latency, $F(1, 15) = 2.434$, $p > .05$, $\eta^2 = .140$; wayfinding accuracy, $F(1, 15) = .072$, $p > .05$, $\eta^2 = .005$; wayfinding efficiency, $F(1, 15) = .142$, $p > .05$, $\eta^2 = .009$.

The combined results of Experiments 1 and 2 provide evidence for a novel explanation with respect to our research question of why integrating multilevel building information into a multilevel cognitive map is so challenging. Our findings suggest that it is not the presence of the z-axis offset alone but the combination of the between-floor overlap and the *z*-axis offset that leads to difficulties in integrating cross-level spatial knowledge.

One might ask, why are problems necessarily caused by this combinatorial effect? Even if challenges in cross-level behavioral performance cannot be solely attributable to the *z*-axis offset, this does not causally lead to a combinatorial explanation. Isn't it possible that degraded performance and inaccuracies in the development of multilevel cognitive maps are caused by the overlap factor in isolation? The short answer is "no." Becausean overlap-only scenario with no *z*-axis offset is not possible given the physics of our 3D world, one cannot partial out overlap in isolation. However, we can consider a situation with the opposite scenario through cross-experiment comparisons. That is, if we compare the *z*-axis offset only condition (Experiment 1, condition 3) with the z-axis offset and overlap condition (Experiment 2, condition 3), which both have a z-axis offset, we can directly examine the combinatorial effect of the overlap factor.

If the effect of overlap is additive, as we are arguing, then the combination of the z-axis offset and overlap factors (Experiment 2, condition 3) should yield reliably worse performance than the *z*-axis offset only condition

(Experiment 1, condition 3). To address this issue, independent-samples *t*-tests were conducted to compare these conditions for each of the four dependent measures (absolute pointing error, pointing latency, wayfinding accuracy, and wayfinding efficiency).

Results revealed a significant difference in the pointing error and latency between the two conditions, pointing error, $t(30) = -2.205$, $p < .05$ and pointing latency, $t(30) = -2.047$, $p < .05$. Specifically, our results demonstrate that, if both buildings have a *z*-axis offset, participants exhibited greater errors and longer latencies when pointing to between-floor targets located in the overlapped building than in the nonoverlapped building.

Taken together, these results (1) corroborate our findings from Experiment 1 demonstrating that the z-axis factor is not the sole cause of problems of integrating cross-level spatial knowledge, and (2) provide additional evidence to our Experiment 2 findings showing that it is the combination of the z-axis and overlap factors that leads to these challenges and the development of accurate multilevel cognitive maps, rather than the traditional conception of the z-axis in isolation.

With regard to the between experiments comparison of wayfinding performance, no reliable differences were found for the wayfinding accuracy and efficiency measures, which is congruent with the findings observed in Experiment 2. These results suggest that the overlap factor affects human's mental representation of multilevel buildings, but not necessarily impairs their between-floor wayfinding performance. We argue that the absence of a wayfinding effect may have been exacerbated by the limited connectivity of our buildings, as the two floors were connected by only one vertical connector (e.g., elevator), which limits the state space of possibilities for cross-floor route selection.

In the real world, almost all buildings are designed with fully or partially overlapped floors, meaning that the between-floor overlap property is one of the most prominent topological characteristics of multifloor buildings. Results of the current study indicate that it is more difficult to maintain the spatial relation of objects between overlapped floors than nonoverlapped environments, revealing that there is a trade-off between the benefits of overlapped floors (e.g., efficient use of land space) and the increased cognitive difficulty of forming a multilevel cognitive map, which should be taken into consideration by architects and urban planners. This trade-off pits practical issues of land use and resource efficiency against the cognitive efficiency of the human user, a problem that is not easily solved and thus likely to remain a challenge for indoor navigation.

Results from Experiment 2 also showed that it is more difficult for people to build a globally coherent mental representation when two incongruent floors of a multilevel building are both overlapped and misaligned (i.e., the reference directions of the two floors have an angular offset). One explanation is that the between-floor misalignment factor violates the assumption that the organization of a given floor extends to all floors (Carlson et al., 2010; Hölscher et al., 2012). This is another mismatch between cognitive factors and architectural factors, as from a design standpoint, there is no such assumption. Indeed, the converse may be true, as designing different floors to be distinct from each other makes the building look less "cookie-cutter" and boring from an aesthetic standpoint. However, from a spatial cognition perspective, this is challenging as navigators have to integrate misaligned cross-level spatial knowledge into a multilevel cognitive map based on the path integration process.

In addition, the misalignment factor caused a portal-floor heading shift on the second floor in the current study, meaning that the between-floor connectivity information was also affected. Thus, users' between-floor wayfinding performance was also undermined in the misaligned conditions relative to the aligned conditions. These findings offer two important implications for architectural design: (1) when a multilevel building has no between-floor visual access, the design and implementation of misaligned floors should be avoided, and (2) a common spatial reference frame between floors is critically important for navigators to build a multilevel cognitive map.

3.3. *Experiment 3*

In Experiment 1, we found that the 90° between-floor heading shift does not impair the development of multilevel cognitive maps. As shown in Figure 5, all four buildings of Experiment 1 were nonoverlapped and shared a common reference direction. We postulated that navigators in Experiment 1 could use interior features to learn this common reference direction, which could be used to complement the path integration process.

However, according to the framework of multilevel cognitive map development proposed here, the confusing heading shift imposed by vertical transitions would increase the difficulty of path integration and subsequently impair users' development of multilevel cognitive maps. In addition, our framework also suggests that the portal-floor angular offset would influence users' cross-floor information integration process.

To address this issue in Experiment 3, we investigated whether a more confusing heading shift (the combined factor of between-floor heading shift α and portal-floor heading shift β, which we refer to as misaligned portals) would impair users' development of multilevel cognitive maps.

3.3.1. *Method*

Sixteen new participants (eight females and eight males, mean age = 20.2, *SD* = 1.2) were recruited from the University of Maine student body. We used the same software package and experimental apparatus as in Experiments 1 and 2.

We designed two overlapped and aligned virtual buildings, as pictured in Figure 13. The experimental procedure was the same as Experiments 1 and 2, except that the elevator used in Experiment 3 had both a 90° between-floor heading shift and a 45° portal-floor angular offset, as shown in Figure 13.

As described in the proposed framework, navigators have to deal with three rotations in the process of vertical transition: (1) portal-floor heading shift I (*β1*): angular offset between floor 1 and the elevator entrance, (2) between-floor heading shift (*α*): angular offset between the elevator entrance and the exit, and (3) portal-floor heading shift II (*β2*): angular offset between floor 2 and the elevator exit. Thus, the extra turn during vertical transition in Experiment 3, compared with Experiment 1, is the turn when participants entered the elevator, which is the portal-floor heading shift I. In addition to this difference, the portal-floor heading shift II of Experiment 3 (*β2* = 45°) is different from that of Experiment 1 (*β2* = 90°).

3.3.2. *Results and discussion*

The means and standard errors for all dependent measures, separated by portal-floor heading shift for Experiment 3, are provided in Appendix Table B3. A one-way repeated measures ANOVA was run for each of the four dependent measures (absolute pointing error, pointing latency, wayfinding accuracy, and wayfinding efficiency), with one within-subject factor of misaligned portals (the combined factor of between-floor heading shift and portal-floor heading shift). No effect was found for any of the four measures: absolute pointing error, $F(1, 15) = .888$, $p > .05$, $\eta^2 = .056$; pointing latency, $F(1, 15) = 3.319$, $p > .05$, $\eta^2 = .181$; wayfinding accuracy, $F(1, 15) = 1.667$, $p > .05$, $\eta^2 = .100$; or wayfinding efficiency, $F(1, 15) = 1.883$, $p > .05$, $\eta^2 = .112$.

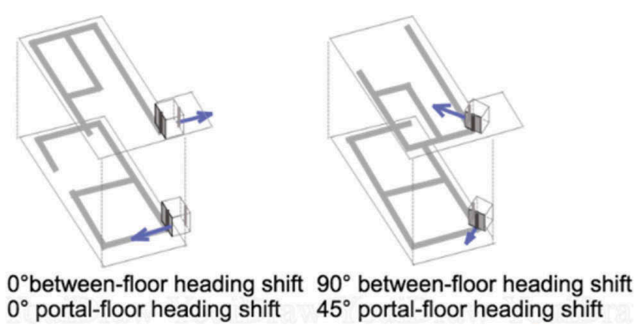

Figure 13. Floor layouts of Experiment 3. The right panel illustrates that the direction of the elevator's entrance has a 45° offset with respect to the reference direction of the floor, which is termed a 45° portal-floor heading shift.

No effects of a confusing heading shift on the pointing error and pointing latency were observed, indicating that the misaligned portals factor did not significantly increase cognitive load for users to develop accurate multilevel cognitive maps, at least when the tested buildings were aligned and shared a common spatial reference. Based on the observed effect sizes, we used G*power to determine how many subjects would have been necessary for statistical significance at a power level of .95. We found that detection of reliable differences would be expected if the sample size was increased to 28 for pointing latency and 280 for pointing error. Simply put, the effect of misaligned portals on between-floor pointing error and pointing latency would likely exist, as we a priori predicted, if different buildings or measures were used, but the effects were not observed in the current study.

These findings offer important implications for architectural design: if two floors are aligned and share a common spatial reference frame, confusing heading shifts (with both a between-floor heading shift and a portal-floor heading shift) may not necessarily cause navigators to get disoriented after vertical travel. However, these type of confusing vertical connectors should be used with caution, as they may increase cognitive effort required to perform spatial computation given that the observed effect size of pointing latency was rather high.

4. General discussion

The goal of the present studies was to investigate cognitive map development during vertical travel in multilevel built environments. In our previous research, we argued that people form a globally coherent mental representation, termed a multilevel cognitive map, to efficiently perform between-floor spatial tasks, e.g., pointing and navigating to destinations located on different floors in a complex building (Li & Giudice, 2012). In the current research, we further defined multilevel cognitive maps as consisting of: (1) a set of single-level cognitive maps, (2) between-floor connectivity information, (3) between-floor alignment information, and (4) encoding of the z-axis. In this article, we described three experiments using desktop VEs to examine the effects of five environmental properties on humans' cognitive map development, including (1) *z*-axis offset, (2) between-floor overlap, (3) between-floor misalignment, (4) between-floor heading shift, and (5) portal-floor heading shift.

The obvious benefit of employing desktop VEs for this research is that they make it relatively easy to parametrically vary properties of the simulated environment and to investigate how manipulating these environmental properties affect humans' mental representations. Performing these environmental manipulations would be difficult, if not impossible, in controlled physical spaces. There are, however, several limitations of these desktop VE-based systems that should be noted. For instance, compared to the experience in physical environments, navigators in desktop VEs experience the "world" with a smaller field of view, lower resolution, less realism than the real world, and often with no auditory, tactile, or proprioceptive (vestibular and kinesthesis) cues (Loomis, Blascovich, & Beall, 1999). The lack of proprioceptive cues in desktop VEs during vertical travel may cause participants to have particular difficulty in accurately perceiving transitions between floors, which could be of concern in studying the integration of cross-level spatial knowledge, as is our focus here.

Nevertheless, given the benefit of ready manipulation of environmental properties that would otherwise be impossible to manipulate in physical environments, as well as the low risk of simulator sickness, desktop VEs are the most feasible approach for studying our core research questions of interest. To address the transition issue in the current research, participants used elevators instead of stairways to reduce additional rotation during interfloor transitions. The entrances of elevators in the VEs were semitransparent, meaning that participants received optic flow cues during vertical travel to clearly convey the inter-floor transitions. We believe that by avoiding the potential pitfalls that have been suggested as complicating vertical travel in desktop VEs, combined with the continually improving quality and realism of renderings, similar cross-level spatial behavioral performance should be obtainable for the real world and desktop VEs in multilevel built environments.

The most important findings from Experiments 1 and 2 are that it is not the presence of the z-axis offset alone, but the combination of the between-floor overlap and the *z*-axis offset that leads to difficulties in developing a globally coherent mental representation of multilevel buildings. Our current findings are consistent with the results of previous research (Giudice & Li, 2012; Li & Giudice, 2013b; Montello & Pick, 1993; Street, 2012), where a between-floor effect was found (i.e., navigators are significantly less accurate when pointing and navigating to locations between floors than within a single floor). Importantly, the finding from Experiment 1 is also consistent with the finding in the research of Montello and Pick (1993), in which participants' pointing performance within a single-floor was comparable for pointing to the targets located on the same floor but at different elevations.

Previous literature has postulated that the between-floor effect could not be attributable to the z-axis offset alone (Montello & Pick, 1993). Our research extends these theories and provides new empirical evidence with respect to the effect of the z-axis offset and overlap on the observed between-floor effect. Specifically, our results reveal that if the within- and between-floor routes have the same level of complexity, whether the between-floor effect is observed depends on whether the two floors are overlapped rather than the z-axis offset alone. In the aforementioned studies (Giudice & Li, 2012; Li & Giudice, 2013b; Montello & Pick, 1993; Street, 2012), the between-floor effect was observed, e.g., users required longer times and exhibited greater errors when pointing to targets located on different floors (or routes) than when they were on the same floor. All buildings in these studies were overlapped with incongruent floor layouts. By contrast, in our Experiment 1, the between-floor effect was not observed, and the two floors with different *z*-axis values were not overlapped.

One might argue, if two regions are overlapped, it becomes more difficult to infer the direction relation between points based on the two regions, as illustrated in the introduction. On this basis, one might ask, is pointing in overlapped buildings generally more difficult than nonoverlapped buildings, due to the nullification of a "region strategy" rather than the poorly developed multilevel cognitive map? A multilevel cognitive map consists of between-floor alignment information (i.e., a finite collection of paired places between a place p_i on floor A and the vertical projection of p_i on floor B, denoted as p_j). Thus, no matter whether participants used the "region strategy" (i.e., inferred the direction relation between points based on ancestor regions) or not, if the between-floor alignment information learned in overlapped buildings is worse than nonoverlapped buildings, we can conclude that the overlap factor (with *z*-axis offset) impairs users' multilevel cognitive map development. However, the question remains, if participants did not use the "region strategy" in nonoverlapped buildings, whether the effect of overlap on between-floor pointing would still be observed? We will investigate this important research question in future studies.

Likewise, some might argue, if two regions are overlapped, the horizontal distance between targets becomes shorter, as shown in Figure 7. Is pointing in overlapped buildings more difficult than nonoverlapped buildings due to shorter horizontal distance between targets? If this is true, there is an alternative explanation for the overlap effect. To address this issue, we first analyze how to control these three factors of pointing distances, route distances, and route turns. As illustrated in Figure 14 (left), we imagine two

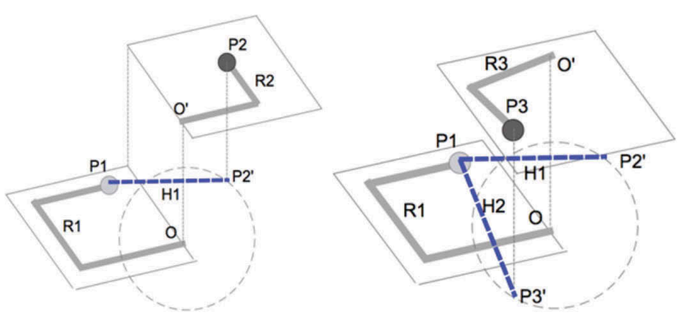

Figure 14. The control of pointing distances, route distances, and route turns. Left (control condition): two routes R1 (on floor 1) and R2 (on floor 2) are connected at O on floor 1 and O′ on floor 2. Right: The route on floor 2 (denoted as R3) is based on the rotation of R2 around O′.

routes are located on two floors. When one route is rotated around one point, as shown in Figure 14 (right), the horizontal distance between any two points in the two routes will change but the route distance remains the same.

If the horizontal distance from P1 to P2′ (denoted as H1) equals the horizontal distance from P1 to P3′ (denoted as H2), both travelled route distances and pointing distances between the two conditions are equaled. However, route turns between the two conditions are mismatched, as based on the proposed framework in this article, the between-floor transition offset of routes R1 and R2 (control condition) is more difficult than routes R1 and R3. Thus, we acknowledge the limitation of our current study in that we did not control both route distances and between-floor pointing distances. However, given that disentangling all three aforementioned factors is geometrically challenging, and that we primarily focused on the two factors of between-floor overlap and misalignment in Experiment 2, we deem that the current experiment is a useful step stone for future studies. The important research question of whether the overlap effect was due to between-floor horizontal distance will be investigated in future.

An alternative explanation of the phenomenon that pointing in nonoverlapped buildings outperformed pointing in overlapped buildings is that two nonoverlapped floors can simply be conceptualized as a single-level floor with different elevations, which was easier to learn than a multilevel building. If this assertion is true, the findings from the current experiments provide further empirical evidence for Jeffery et al. (2013)'s bicoded model, in which they argue that human spatial representation of 3D space comprises a set of locally planar bicoded map fragments rather than a fully integrated volumetric map. However, we are still skeptical of their conclusion that humans do not have the capacity of constructing true 3D spatial representations in the brain. We argue that this might be due to the scale of 3D spaces. According to Montello (1993), a room represents an example of a vista space, as one sees the entire spatial extent from a single vantage point with head rotation. Most floors of buildings, however, have to be perceived by moving through the space and thus, by definition, are environmental spaces. The environmental space scale of multilevel buildings as well as the "layer by layer" navigation pattern may determine that users' formed mental representations are better conceptualized as a multilayered structure rather than a true 3D mental representation.

We are not arguing that the relation between overlapped floors and the between-floor effect is causal, because other factors such as route complexity, landmarks, and visual access between locations must also be taken into consideration. However, results from Experiments 1 and 2 provide clear evidence that the between-floor overlap reliably increased the difficulty of between-floor pointing and wayfinding performance, even though the between- and within-floor routes had the same length and number of turns as well as visual access between locations. Thus, we advocate that future research should address the role played by between-floor overlap on path integration and multilevel cognitive map development. The findings of future studies may shed important light on human mental representation in three dimensions.

Results from Experiment 2 also demonstrated that the between-floor misalignment substantially led to increased challenges in developing accurate multilevel cognitive maps. This finding is consistent with, and extends, previous research regarding the evaluation of misalignment of a single floor on users' cognitive map development (Werner & Schindler, 2004). The Werner & Schindler study (2004) was also based on use of desktop VR, in which the region around the elevator was 45° misaligned with respect to the rest of the floor. The average pointing error in the misalignment of a single floor was 46° in the Werner & Schindler study (2004). By contrast, in our current study, the average pointing error in misaligned multilevel buildings was 80°. This surprisingly high pointing error is likely due to participants needing to integrate two overlapped floors in order to accurately obtain rotational displacements during vertical travel. As discussed before, the between-floor overlap was found to increase the difficulty of developing accurate multilevel cognitive maps. Thus, the process of learning overlapped and misaligned buildings may yield increased cognitive load compared to the same process when integrating multiple misaligned regions on a single floor. This finding is consistent with previous literature regarding indoor wayfinding and mental representation, which suggests that a multilevel cognitive map consists of a set of super-imposed single-level cognitive maps (Hölscher et al., 2006; Vidal, Amorim & Berthoz, 2004). Furthermore, the finding from Experiment 2 extends previous literature in that, in addition to a set of single-level cognitive maps, between-floor alignment information also plays an important role in forming multilevel cognitive maps. For instance, findings from Experiment 2 provide important evidence that when there is a between-floor perspective shift (γ = 45°), the difficulty of building a multilevel cognitive map is substantially increased.

Previous literature has pointed out that confusing staircases are a main cause leading to people getting lost in buildings (Hölscher et al., 2006). However, based on the results from Experiment 3, no solid empirical evidence was found that confusing between-floor heading shifts impede users' development of multilevel cognitive maps in aligned buildings, at least as the sole determining factor. However, the interaction between confusing heading shifts and misaligned floors may contribute to people getting lost in buildings, an issue that will be further investigated in future studies.

These findings also offer some important implications for architectural design. For example, when a multilevel building has no between-floor visual access, the design and implementation of misaligned floors should be avoided to the maximum extent, and a common spatial reference frame between floors should be designed. For instance, the common spatial reference frame can be created by making an atrium, which affords between-floor visual access and helps navigators construct a common reference frame. On the other hand, when a multilevel building has no between-floor visual access, confusing heading shifts, especially those incorporating both a between-floor heading shift and a portal-floor heading shift, should be used with caution. If confusing heading shifts are deemed necessary for aesthetic reasons or usage considerations, the vertical connectors such as staircases should be situated in an open area with good between-floor visual access (e.g., by removing the stairwell, making the walls transparent, or using glass elevators).

These implications are derived from a cognitive psychology perspective and are difficult and often impractical to implement. In the real world, almost all buildings are designed with fully or partially overlapped floors for efficient use of land space. In addition, substantial numbers of public buildings (e.g., the Seattle public library) are intentionally designed with incongruent floor layouts, misaligned floors, and confusing staircases for aesthetic reasons. The findings of the current experiments should not be interpreted as suggesting that every building should be flat and boring. Instead, we argue that there is a trade-off between the benefits of efficient land use, aesthetic consideration, occupant usage, and the increased difficulty of learning a building that are worthy of consideration. These trade-offs and balance between competing factors are a challenge for urban planners and architects to consider more carefully.

The current findings are based on situations where the multilevel building has no between-floor visual access and no visual access between outdoor and indoor spaces (O/I spaces). Previous literature has indicated that the limited visual access inside buildings is a significant cause of indoor wayfinding difficulties (Giudice, Walton, & Worboys, 2010; Hölscher et al., 2006; Weisman, 1981). We postulated that increasing visual access between floors and between O/I spaces would help mitigate the challenge. In the physical world, increasing visual access through structural modifications is impractical. However, we proposed that improved visualization interfaces could assist users in developing more accurate multilevel cognitive maps.

In support of this hypothesis, Li, Corey, Giudice, and Giudice (2016) conducted a series of experiments using VEs to investigate whether increasing visual access to global landmarks (i.e., those visible from multiple locations/floors of a building) would assist the development of multilevel cognitive maps. In these studies, participants first learned a multilevel virtual building with the assistance of different visualization interfaces providing access to global landmarks. They then took part in three cross-floor spatial tasks including pointing and wayfinding between floors and a cross-floor drilling task. Results demonstrated that increasing visual access to a global landmark through an X-ray visualization is an effective way for overcoming the disadvantage of limited visual access in built environments and significantly improving the development of multilevel cognitive maps. We believe that with the advancement of augmented reality technology and intelligent wearable devices, better between-floor visual access and visual access between O/I spaces will become possible in the near future. Benefit from this creative technological solution to architectural design will make our built environments more exciting and inspiring without contributing to the problem of further confusing and disorienting navigators.

In sum, our take-home argument based on the current results is that when representing multilevel environments without clear perceptual access between layers, people build a multilevel cognitive map of the space, rather than developing multiple super-imposed single-level cognitive maps without any vertical transition or alignment information. Whether the multilevel cognitive map proposed here is just an intermediate step leading to a more comprehensive true 3D representation will be addressed in future research.

Acknowledgments

The authors are grateful to Dan Montello and three anonymous reviewers for providing valuable suggestions on an earlier version of this article.

Funding

This research was in part funded by the University of Maine Janet Waldron Doctoral Research Fellowship. Work on this project was also partially sponsored by the Future Cities Laboratory at the Singapore-ETH Centre, which was established collaboratively between ETH Zurich and Singapore's National Research Foundation (FI 370074016).

References

Carlson, L. A., Hölscher, C., Shipley, T. F., & Dalton, R. C. (2010). Getting lost in buildings. *Current Directions in Psychological Science*, *19*(5), 284–289.

Downs, R. M., & Stea, D. (Eds.). (1973). *Image and environment: Cognitive mapping and spatial behavio*r. Transaction Publishers.

Etienne, A. S., & Jeffery, K. J. (2004). Path integration in mammals. *Hippocampus*, *14*(2), 180–192.

Gallistel, C. R. (1990). *The organization of learning*. Cambridge, MA: The MIT Press.

Garling, T., Böök, A., Lindberg, E., & Arce, C. (1990). Is elevation encoded in cognitive maps? *Journal of Environmental Psychology*, *10*(4), 341–351.

Giudice, N. A., & Li, H. (2012). The effects of visual granularity on indoor spatial learning assisted by mobile 3D information displays. In C. Stachniss, K. Schill, & D. H. Uttal (Eds.), *Spatial Cognition VIII* (Vol. 7463, pp. 163–172). Kloster Seeon, Germany: Springer.

Giudice, N. A., Walton, L. A., & Worboys, M. (2010). The informatics of indoor and outdoor space: a research agenda. In *Proceedings of the 2nd ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness* (pp. 47–53). ACM.

Hayman, R., Verriotis, M., Jovalekic, A., Fenton, A. A., & Jeffery, K. J. (2011). Anisotropic encoding of three-dimensional space by place cells and grid cells. *Nature Neuroscience*, *14* (9), 1182–1188.

Hölscher, C., Brösamle, M., & Vrachliotis, G. (2012). Challenges in multilevel wayfinding: A case study with the space syntax technique. *Environment and Planning B: Planning and Design*, *39*(1), 63–82.

Hölscher, C., Büchner, S., & Strube, G. (2013). Multi-floor buildings and human wayfinding cognition. *Behavioral and Brain Sciences*, *36*(5), 551–552.

Hölscher, C., Meilinger, T., Vrachliotis, G., Brösamle, M., & Knauff, M. (2006). Up the down staircase: Wayfinding strategies in multilevel buildings. *Journal of Environmental Psychology*, *26*(4), 284–299.

Jeffery, K. J., Jovalekic, A., Verriotis, M., & Hayman, R. (2013). Navigating in a three-dimensional world. *The Behavioral and Brain Sciences*, *36*, 523–587.

Kelly, J. W., & Mcnamara, T. P. (2008). Spatial memories of virtual environments: How egocentric experience, intrinsic structure, and extrinsic structure interact. *Psychonomic Bulletin & Review*, *15*(2), 322–327.

Klatzky, R. L., Beall, A., & Loomis, J. M. (1999). Human navigation ability: Tests of the encoding-error model of path integration. *Spatial Cognition and Computation*, *1*, 31–65.

Klatzky, R. L., & Giudice, N. A. (2013). The planar mosaic fails to account for spatially directed action. *Behavioral and Brain Sciences*, *36*(5), 554–555.

Klatzky, R. L., Loomis, J. M., & Golledge, R. G. (1997). Encoding spatial representations through nonvisually guided locomotion: Tests of human path integration. *Psychology of Learning and Motivation*, *37*, 41–84.

Li, H., Corey, R. R., Giudice, U., & Giudice, N. A. (2016). *Assessment of visualization interfaces for assisting wayfinding in multi-floor buildings*. 18th International Conference on Human-Computer Interaction, Toronto, Canada.

Li, H., & Giudice, N. A. (2012). Using mobile 3D visualization techniques to facilitate multilevel cognitive map development of complex indoor spaces. In C. Graf, N. A. Giudice, & F. Schmid (Eds.), *Proceedings of the International Workshop on Spatial Knowledge Acquisition with Limited Information Displays (SKALID')* (Vol. 888, pp. 31–36). CEUR Workshop Proceedings, Monastery Seeon, Germany.

Li, H., & Giudice, N. A. (2013a). *The effects of 2D and 3D maps on learning virtual multilevel indoor environments*. 1st ACM SIGSPATIAL International Workshop on Interacting with Maps (MapInteract 2013), Orlando, FL, USA (pp. 7–12). ACM.

Li, H., & Giudice, N. A. (2013b). *The effects of immersion and body-based rotation on learning multilevel indoor virtual environments*. 5th ACM SIGSPATIAL International Workshop on Indoor Spatial Awareness (ISA 2013), Orlando, FL, USA (pp. 8–15). ACM.

Loomis, J. M., Blascovich, J. J., & Beall, A. C. (1999). Immersive virtual environment technology as a basic research tool in psychology. *Behavior Research Methods, Instruments, & Computers*, *31*(4), 557–564.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., Cicinelli, J. G., Pellegrino, J. W., & Fry, P. A. (1993). Nonvisual navigation by blind and sighted: Assessment of path integration ability. *Journal of Experimental Psychology. General*, *122*(1), 73–91.

Loomis, J. M., Klatzky, R. L., Golledge, R. G., & Philbeck, J. W. (1999). Human navigation by path integration. In R. G. Golledge (Ed.), *Wayfinding behavior: Cognitive mapping and other spatial processes* (pp. 125–151). JHU press.

McNamara, T. P., Sluzenski, J., & Rump, B. (2008). Human spatial memory and navigation. In H. L Roediger.(Ed.), *Learning and memory: A comprehensive reference: Vol. 2. Cognitive psychology of memory* (Vol. 2, pp. 157–178). Oxford, UK: Elsevier.

Meilinger, T. (2008). The network of reference frames theory: A synthesis of graphs and cognitive maps. In C. Freksa, N. Newcombe, P. Gärdenfors, & S. Wölfl (Eds.), *Spatial cognition VI: Learning, reasoning, and talking about space* (pp. 44–360). Berlin: Springer.

Meilinger, T., Riecke, B. E., & Bülthoff, H. H. (2013). Local and global reference frames for environmental spaces. *Quarterly Journal of Experimental Psychology*, *67*(3), 542–569.

Montello, D. R. (1993). Scale and multiple psychologies of space. In A. U. Frank & I. Campari (Eds.), *Spatial Information Theory: A Theoretical Basis for GIS: European Conference, COSIT'93 Marciana Marina, Elba Island, Italy September 19–22, 1993 Proceedings* (pp. 312–321). Berlin, Germany: Springer Berlin Heidelberg.

Montello, D. R., & Pick, H. L. (1993). Integrating knowledge of vertically aligned large-scale spaces. *Environment and Behavior*, *25*(3), 457–484.

O'Keefe, J. (1991). An allocentric spatial model for the hippocampal cognitive map. *Hippocampus*, *1*(3), 230–235.

O'Keefe, J., & Nadel, L. (1978). *The hippocampus as a cognitive map*. Oxford, UK: Oxford University Press.

Papadias, D., & Egenhofer, M. J. (1997). Algorithms for hierarchical spatial reasoning. *GeoInformatica*, *1*, 1–23.

Passini, R. (1992). *Wayfinding in architecture* (2nd ed.). New York, NY : Van Nostrand Reinhold Company.

Schultheis, H., & Barkowsky, T. (2013). Just the tip of the iceberg: The bicoded map is but one instantiation of scalable spatial representation structures. *Behavioral and Brain Sciences*, *36*(5), 565–566.

Street, W. (2012). *Between floor navigation cost depends on visual information* (master's thesis). Retrieved from http://hdl.handle.net/2142/29487

Tlauka, M., Wilson, P. N., Adams, M., Souter, C., & Young, A. H. (2007). An investigation into vertical bias effects. *Spatial Cognition & Computation*, *7*(4), 365–391.

Tolman, E. C. (1948). Cognitive maps in rats and men. *Psychological Review*, *55*(4), 189–208.

Vidal, M., Amorim, M.-A., & Berthoz, A. (2004). Navigating in a virtual three-dimensional maze: How do egocentric and allocentric reference frames interact? *Brain Research. Cognitive Brain Research*, *19*(3), 244–258.

Wan, X., Wang, R. F., & Crowell, J. A. (2013). Effects of basic path properties on human path integration. *Spatial Cognition & Computation*, *13*(1), 79–101.

Wang, R. F. (2012). Theories of spatial representations and reference frames: What can configuration errors tell us? *Psychonomic Bulletin & Review*, *19*(4), 575–587.

Wang, R. F., & Street, W. N. (2013). What counts as the evidence for three-dimensional and four-dimensional spatial representations? *Behavioral and Brain Sciences*, *36*(5), 567–568.

Weisman, J. (1981). Evaluating architectural legibility: Way-finding in the built environment. *Environment and Behavior*, *13*(2), 189–204.

Werner, S., & Schindler, L. E. (2004). The role of spatial reference frames in architecture: Misalignment impairs way-finding performance. *Environment & Behavior*, *36*(4), 461–482.

Wiener, J. M., & Mallot, H. (2003). "Fine-to-Coarse"Route Planning and Navigation in regionalized environments. *Spatial Cognition and Computation*, *3*(4), 331–358.

Wilson, P. N., Foreman, N., Stanton, D., & Duffy, H. (2004). Memory for targets in a multilevel simulated environment: Evidence for vertical asymmetry in spatial memory. *Memory & Cognition*, *32*(2), 283–297.

Yartsev, M. M., & Ulanovsky, N. (2013). Representation of three-dimensional space in the hippocampus of flying bats. *Science*, *340*(6130), 367–372.

Appendix A

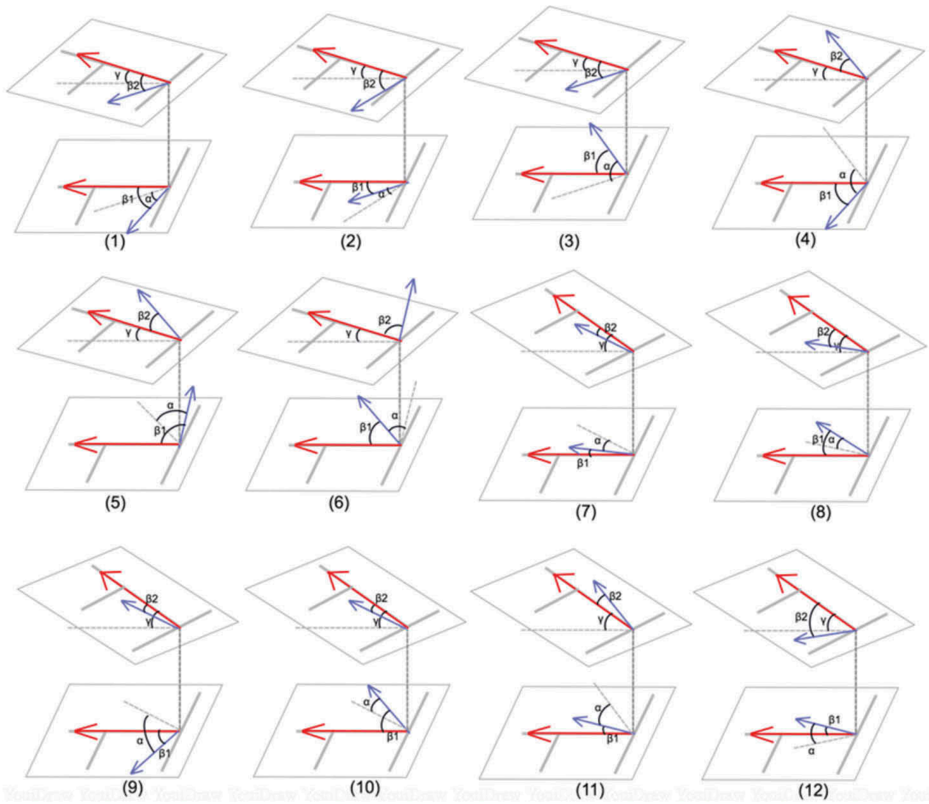

Figure A1. Twelve situations of calculating perspective shifts (*γ*) based on the between-floor heading shift *α* and two portal-floor heading shifts (*β1* and *β2*). For these 12 situations, there are 7 different combinations of calculating perspective shifts (*γ*) based on the between-floor heading shift *α* and 2 portal-floor heading shifts (*β1* and *β2*): (1) $\gamma = \beta 2 - (\beta 1 - \alpha)$, (2) $\gamma = \beta 2 - (\beta 1 + \alpha)$, (3) $\gamma = \beta 2 - (\alpha - \beta 1)$, (3) $\gamma = (\beta 1 - \alpha) + \beta 2$, (4) $\gamma = (\alpha - \beta 1) - \beta 2$, (5) $\gamma = (\beta 1 - \alpha) - \beta 2$, (6) $\gamma = (\beta 1 + \alpha) - \beta 2$, and (7) $\gamma = \beta 2 + (\beta 1 + \alpha)$.

Appendix B

Means and Standard Errors Across Experiments

Table B1. Mean absolute pointing error, pointing latency, wayfinding accuracy, and wayfinding efficiency in Experiment 1.

Dependent Variables (Measures)	Independent Variable II	Independent Variable I	
		No *z*-axis offset	*z*-axis offset
Absolute pointing error	0° between-floor heading shift	25.39 (3.49)	21.58 (4.72)
	90° between-floor heading shift	20.29 (2.94)	22.48 (3.50)
Pointing latency	0° between-floor heading shift	12.48 (1.24)	11.85 (1.21)
	90° between-floor heading shift	12.52 (1.30)	12.32 (1.74)
Wayfinding accuracy	0° between-floor heading shift	71.9% (6.4%)	81.3% (7.7%)
	90° between-floor heading shift	78.1% (6.4%)	75.0% (9.1%)
Wayfinding efficiency	0° between-floor heading shift	70.6% (6.4%)	79.9% (7.5%)
	90° between-floor heading shift	77.4% (6.5%)	73.5% (9.4%)

Table B2. Mean absolute pointing error, pointing latency, wayfinding accuracy, and wayfinding efficiency in Experiment 2.

Dependent Variables	Independent Variable II	Independent Variable I	
		Nonoverlap	Between-floor overlap
Absolute pointing error	Alignment	20.84 (4.48)	38.95 (6.31)
	Misalignment	32.62 (3.77)	80.04 (5.59)
Pointing latency	Alignment	14.70 (2.00)	17.07 (2.24)
	Misalignment	19.80 (2.48)	30.88 (6.88)
Wayfinding accuracy	Alignment	87.5% (5.6%)	87.5% (5.6%)
	Misalignment	75.0% (7.9%)	71.9% (7.9%)
Wayfinding efficiency	Alignment	85.1% (5.6%)	87.5% (5.6%)
	Misalignment	73.3% (7.7%)	71.1% (7.9%)

Table B3. Mean absolute pointing error, pointing latency, wayfinding accuracy, and wayfinding efficiency in Experiment 3.

Dependent Variables (Measures)	Independent Variable I	
	Aligned portals	Misaligned portals
Absolute pointing error	32.22 (4.42)	28.67 (4.05)
Pointing latency	17.17 (2.37)	21.51 (3.62)
Wayfinding accuracy	90.6% (5.0%)	78.1% (7.9%)
Wayfinding efficiency	89.0% (4.9%)	75.9% (8.0%)