Spatial Navigation in a Virtual Multilevel Building: The Role of Exocentric View in Acquiring Survey Knowledge

Zhiqiang Luo[1], Henry Been-Lirn Duh[2],
I-Ming Chen[1], and Wenshu Luo[3]

[1] Sch. of Mech. & Aerospace Enginerring, Nanyang Technological University, Singapore
`zqluo@ntu.edu.sg`, `michen@ntu.edu.sg`
[2] Dept. of Electrical & Computer Engineering, National University of Singapore, Singapore
`eledbl@nus.edu.sg`
[3] Centre for Research of Pedagogy and Practice, National Institute of Education, Singapore
`wenshu.luo@nie.edu.sg`

Abstract. The present study aimed to test the function of the exocentric view on the acquisition of survey knowledge during spatial navigation in a virtual multilevel building. Subjects navigated a virtual three-level building in three conditions. In the first condition, subjects navigated the building without any aid. In the second condition, subjects navigated the building with the aid of a three-dimensional (3D) floor map which illustrated the spatial layout on each level from one exocentric perspective. In the third condition, subjects could watch the spatial layout on each level from the exocentric perspective when traveling to another level by an elevator. After navigation, all subjects made the judgment of spatial relative direction. The analyses of the accuracy of spatial judgments showed that the accuracy of judgment of spatial horizontal direction was significantly improved when subjects observed the exocentric views of levels in the last two conditions; the judgment of spatial vertical direction was significantly worse in the 3D floor map condition than in other two conditions. Furthermore, the accuracy of judgment of both spatial horizontal and vertical directions was best in the direction faced by subjects when they first enter each level. The results suggested that the content of exocentric view should be carefully designed to improve the acquisition of survey knowledge. The application of the findings included the design of 3D map for the navigation in the virtual multilevel building.

1 Introduction

Spatial navigation in a multilevel building is one common task in people's daily life, such as the navigation in the subway station, shopping mall and the museums. A multilevel building is a constrained three-dimensional (3D) space with the constraints of walls, ceilings and floors. Navigation in a multilevel building is also limited within specific areas, such as on floors and staircases. Because of the constraints of building and navigation, it is very difficult for people to acquire the accurate survey knowledge of a multilevel building. When navigating the multilevel building in the virtual

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environment (VE) rather than in the real world, people encounter more problems in acquiring the survey knowledge. Previous studies [4, 13] have demonstrated that the exocentric views provided during the navigation on the level in one virtual building can facilitate the acquisition of survey knowledge of spatial layout in this level. Two questions are addressed in the present study: (1) Do the exocentric views facilitate the acquisition of survey knowledge in a virtual multilevel building; (2) what difference exists in survey knowledge if the way to provide the exocentric views is different during spatial navigation in the same virtual multilevel building.

Generally, there are two common ways to provide the exocentric views during spatial navigation in VE. The first way is to elevate the viewpoint in air. For example, subjects in study [13] study learned a virtual floor layout of building with one of three navigation training aids: local and global orientation cues, exocentric views, and a theme environment enhanced with sights and sounds, where subjects with the exocentric-view aid watched the layout from a viewpoint outside the building. The survey knowledge was tested after the navigation. The results indicated that the exocentric views were effective in improving performance on the survey knowledge tests. One extreme exocentric view of environment is a 3D model of environment, such as "world in miniature" (WIM, [10]) which can be changed at will simply by rotating or zooming in study [4] employed a 3D model of one floor of a building to assist their subjects' spatial learning, and the results indicated that this modal was even as good as a real-world environment for acquiring survey knowledge. Furthermore, they suggested that a VE training system that combines an immersive walk-through VE and a miniature-model VE could provide better training to achieve the survey knowledge than real-world training.

The second way is to draw the exocentric view of space into a 3D map, or called the exocentric map, on a computer screen or a paper. Compared with the 2D map, the 3D map preserves features of objects and integrates all three dimensions into a single rendering, thereby enhancing the shape and layout understanding [11]. Evidence for the benefits of the 3D map comes from the research on aviation displays for navigation in the unconstrained 3D natural space [3, 12] and the research on learning the building structure in the constrained building space [2]. For example, Fontaine [2] found that subjects using a 3D map could better elaborate the vertical relations between levels of a subway station than their counterparts without the map.

Although spatial learning from the exocentric views can facilitate the acquisition of survey knowledge, the orientation-dependent mental representation is still observed. Subjects in study [9] study learned the spatial layout on one floor in a large-scale virtual building environment from either the egocentric or exocentric perspective, and then performed the judgment of relative direction (JRD ,"Imagine you are standing at object A and facing object B, point to object C"). The accuracy of spatial judgment indicated that subjects judged the relative directions between objects more accurately when imagining facing the direction aligned with the initial orientation faced in this building. The experience of exploring spatial layout plays a critical role in defining the orientation-dependent property of mental representation of this environment [6].

The present study aimed to test the function of the exocentric view on the acquisition of survey knowledge of a virtual multilevel building. The exocentric view was acquired through the above two ways, the elevation of viewpoint in air and the 3D map. Specifically, the first way was realized by permitting subjects to observe the floor layout from the exocentric perspectives when they took the elevator to travel between levels in this multilevel building. The second way was to provide the 3D floor map which draws the floor layout from one exocentric perspective. The content of the 3D floor map would be updated when subjects arrive at a new level in this multilevel building.

Three hypotheses would be tested in this study. First, the exocentric views provided by above two ways could facilitate the acquisition of survey knowledge in the virtual multilevel building. Second, there was no difference between the survey knowledge when the exocentric views were provided by these two ways. Third, orientation dependent mental representation of the virtual environment would be build even though the exocentric views were provided during the spatial navigation.

2 Participant

Thirty undergraduate and graduate students (15 males, 15 females, all between 18 and 29 years of age, M =22, SD = 2.586) from Nanyang Technological University in Singapore participated in this experiment for monetary compensation. All participants had normal or corrected-to-normal vision.

3 Materials

A HP xw4300 workstation with a 19-in LCD monitor was used to display virtual environments (VEs) which were created by using EON software (Eon Reality Company, 2004). Movement through the VE was effected by pressing the arrow keys on the keyboard: the up and down arrows effected forward and backward movements, whereas the left and right arrows effected left and right rotations. Subjects could hold down the keys to obtain the continuous translation with 1 meter per second and rotation with 60^0 per second.

The multilevel VE was comprised of three vertically aligned rooms that formed a three-level building (see Figure 1). The room on each level was rectangular in shape and measured approximately 8m×6m×3m. In the middle of one of the shorter walls on each level was an elevator with a 2×2m floor, which connected the adjacent levels. The elevator had one door which was open to the room and close when the elevator moved between levels. In all but one experimental condition, the doors were opaque and subjects could not observe the outside when taking the elevator. Inside the elevator room, subjects could choose the target level by clicking on a level button. There were nine common household objects (e.g. chair, cabinet, etc) in the experimental building, three positioned in different locations in each room.

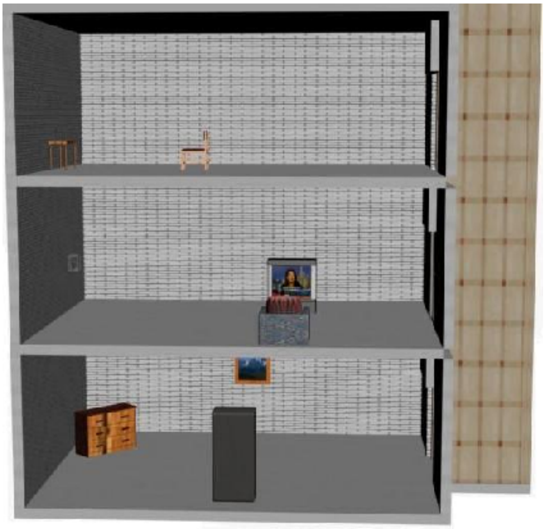


Fig. 1. The virtual three-level building

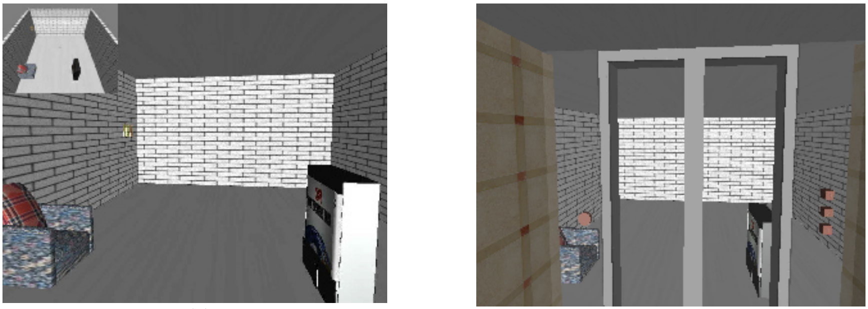
4 Design

The independent variables included one between-subjects variable and two within-subjects variables. The between-subjects variable defined three kinds of navigation treatment: no map, 3D floor map, and transparent conditions. Subjects were randomly assigned to each of three experimental conditions. The no map group was the control group, in which subjects explored the virtual building without any aid.

The 3D floor map presented the layout of each level from the viewpoint of 4 meters above that level, looking forward from the elevator. The geometric field of view (GFOV) of the exocentric map was set at 74^0 on the horizontal axis and 59^0 on the vertical axis to help with the depiction of spatial layout and to assist subjects with the position judgment.

In the 3D floor map condition, a small (10.2cm×8.1cm) map was embedded in the 3D immersive view and located in the top left of the computer screen. This method was based on the split-screen technique used in the design of aviation display (e.g., [7]). This design allowed subjects to go back and forth easily and quickly between exocentric views of maps of space and egocentric views derived from being in that space, which was effective for remaining oriented and learning the space. Specifically, the 3D floor map showed the layout of the level on which subjects were standing. When subjects arrived on a new level by taking the elevator, the content of map automatically changed to show the new level layout. The view of the second level in the 3D floor-map condition is shown in Figure 2(a).

In the transparent condition, the elevator door and its connected wall were transparent so that subjects could observe the room layout through the door when standing inside the elevator. The virtual building was not augmented with any map aid. But different from the no map condition, subjects in this condition could observe the room



(a) (b)

Fig. 2. The view of second level in (a) the 3D floor map condition and (b) the transparent condition

layout from exocentric perspectives as elevation changed. The view of the second level in the transparent condition is shown in Figure 2(b) when subjects took the vertical move between the second and third levels.

The two within-subjects variables defined the characteristics of probe questions to be asked in the judgment of relative direction task (JRD, “Imagine you are standing at object A and facing object B, point to object C”,[1]): (1) the level difference between the target objects C and the reference objects A and B and (2) the imagined facing direction from object A to object B. The level difference along the vertical dimension could be two levels up, one level up, same level, one level down, two levels down, designed to reveal the vertical same level bias and downward bias in spatial memory. The imagined facing direction along the horizontal dimension could be forward (facing the room from the elevator), left/right, or backward (facing the elevator from the room), purported to reveal the preferred orientation in spatial memory.

To perform the JRD task, subjects were required to stand at one mark which was 1 meter in front of a vertically mounted board. A coordinate system was set up in this test environment. The original point of this coordinate system was the mark on the ground, the Z axis was defined to be vertical to the ground, the Y axis paralleled the front board, and the X axis was orthogonal to the front board. Therefore, each position in the test environment could be represented by a coordinate of this system (x, y, z). Moreover, the target object C in the JRD task were all in front of subjects as they imagined facing the reference object B, so subjects would not need to point to objects behind them. Subjects were required to use a laser pointer to project a point on the board, through which they could imagine seeing the top of the target assigned in the instruction. The experimenter recorded the coordinates of the eye and the point on the board. From this, the horizontal and vertical angles between the eye and the point in the coordinate system could be computed.

In this test, the dependent variables were the angular error and the response time. The angular error was measured as the absolute angular difference between the pointing direction and the actual direction where the target would have been. There were two angular errors: the error of horizontal angle and the error of vertical angle. The response time was measured as the time from the presentation of instruction to the end of the subject's response, which was recorded by a stop watch.

5 Procedure

Subjects were tested individually in a quiet room. In order to screen out subjects with the poor memory, all subjects first took a memory test. They were required to scan nine objects printed on a piece paper for 30 seconds and then generate these objects at the corresponding positions on a piece of blank paper with the same size. These nine objects were not used in the virtual building. All subjects could recall more than six objects in this test and were allowed to proceed to the next phase.

Subjects were then seated approximately 0.42 meters from the computer screen. They first observed the nine experimental objects printed as 3D objects on a piece of paper. After they were familiar with the objects and could associate each with a unique name, they started practicing the navigation in a practice building containing no objects. The practice building was the same as the experimental building except the spatial objects. Maps were not given to subjects in the 3D floor map condition at this moment and no time limit was imposed on this preliminary exploration. Subjects then navigated the experimental building with nine objects. They were told that each of nine objects would react if clicked by the mouse and they needed to go nearby to the objects to click on the objects. Subjects were instructed to explore all three levels freely in ten minutes and enter each room at least twice. They were told that the purpose of this exploration was to remember the locations of the nine objects and that they would later be asked to point out these locations.

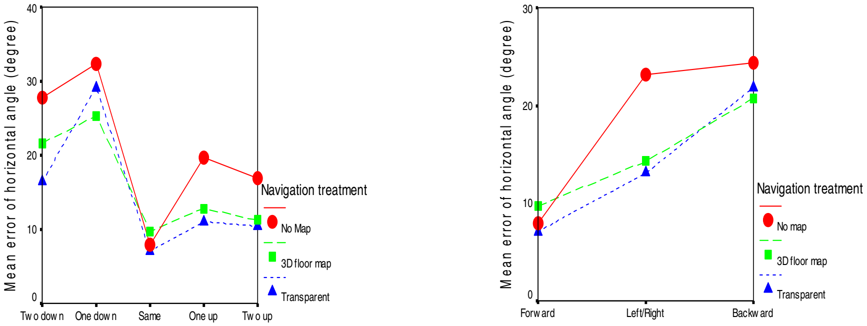
After exploring the building, subjects were asked to perform the JRD task. The instruction of each trial was displayed on the computer. Subjects first took two trials in order to be familiar with the requirement and procedure of the JRD task. The performance in these two trials was not counted in the data analysis. The total time for the experiment was approximately 60 minutes.

6 Result

All dependent measures were subjected to analysis of variance (ANOVA) in terms of navigation treatment, level difference and imagined facing direction. Since the levels of the two within-subjects variables were not fully crossed, the interaction between them could not be tested. Therefore, in the customized analysis, only the main effects of the three independent variables and the interaction effects between navigation treatment and each of the two between-subjects variables were examined. A significance level $\alpha < .05$ was adopted for all these analyses.

6.1 The Judgment Accuracy of Horizontal Direction

The main effect of the navigation treatment was significant, $F(1, 27) = 3.82$, $p < .05$. Multiple comparisons showed that the performance was significantly worse in the no-map condition than in other two conditions; the remaining two did not differ



(a)

(b)

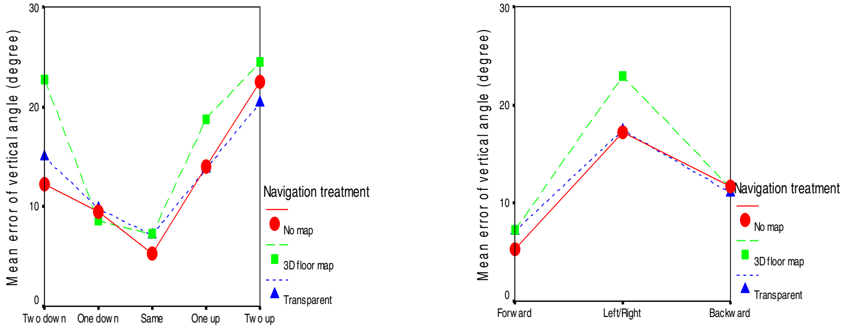
Fig. 3. Judgment of the horizontal direction. (a) Mean error of horizontal angle as a function of level difference and navigation treatment; (b) Mean error of horizontal angle as a function of imagined facing direction and navigation treatment.

significantly. As depicted in Figure 3(a), the main effect of level difference was significant, $F(4, 108) = 19.23$, $p < .01$. Multiple comparisons showed that (1) the best performance (least error) was observed when subjects pointed to objects on the same floor, and (2) the performance was better when pointing up than pointing down. The interaction between navigation treatment and level difference was not significant.

As depicted in Figure 3(b), the main effect of the imagined facing direction was significant, $F(2,54) = 41.80$, $p < .01$. Multiple comparisons suggested that the performance in the forward direction (i.e. the orientation from which subjects entered the room) was the best and in the backward (i.e. the orientation from which subjects exited the room) was the poorest. The interaction between navigation treatment and imagined facing direction was also significant $F(4,54) = 2.60$, $p < .05$. Further analyses in each navigation condition revealed that (1) in the no-map condition, the performance in the forward direction was better than those in the left/right and backward directions; (2) in the 3D floor map condition, the performance in the forward direction was better than those in the backward direction, while no significant difference was found between the left/right direction and other two directions.; (3) in the transparent direction, the performance was best in the forward direction, then in the left/right direction, and poorest in the backward direction.

6.2 The Judgment Accuracy of Vertical Direction

The main effect of the navigation treatment was significant, $F(1, 27) = 4.37$, $p < .05$. Multiple comparisons showed that the performance was significantly worse in the 3D floor map condition than in other two conditions; the remaining two did not differ significantly. As depicted in Figure 4(a), the main effect of level difference was significant, $F(4, 108) = 20.64$, $p < .01$. Multiple comparisons showed that (1) the best performance (least error) was observed when subjects pointed to objects on the same floor, and (2) the performance was better when pointing down than pointing up. The interaction between navigation treatment and level difference was not significant.



(a) (b)

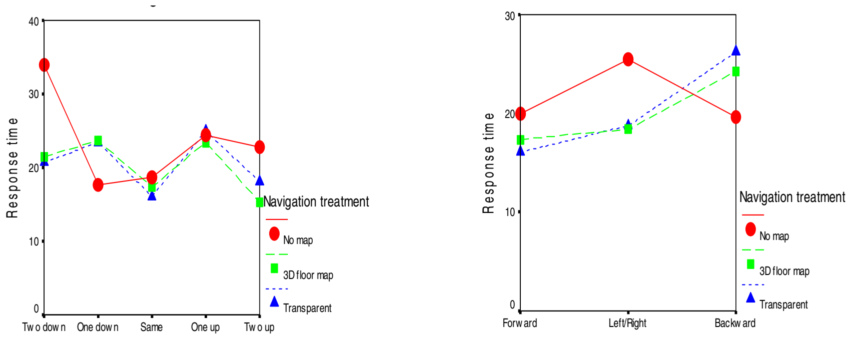
Fig. 4. Judgment of the horizontal direction. (a) Mean error of vertical angle as a function of level difference and navigation treatment; (b) Mean error of vertical angle as a function of imagined facing direction and navigation treatment.

As shown in Figure 4(b), the main effect of the imagined facing direction was significant, $F(2,54) = 52.78$, $p < .01$. Multiple comparisons suggested that the performance in the forward direction (i.e. the orientation from which subjects entered the room) was better than those in other two directions. The interaction between the imagined facing direction and the navigation treatment was not significant.

6.3 Response Time

Navigation treatment did not show significant main effect on response time. There was a significant effect of level difference, $F(4, 108) = 4.22$, $p < .01$, and pointing to objects on the same level was fastest, as shown in Figure 5(a). The interaction between navigation treatment and level difference was not significant.

As shown in Figure 5(b), the main effect of the imagined facing direction was significant, $F(2, 54) = 6.749$, $p < .01$. The interaction between navigation treatment and



(a) (b)

Fig. 5. Response time. (a) Response time as a function of level difference and navigation treatment; (b) Response time as a function of imagined facing direction and navigation treatment.

imagined facing direction was significant, $F(4, 54) = 3.98$, $p < .05$. Post hoc analysis showed that only in the no map condition was the response time affected by imagined facing direction, suffering most when subjects imagined facing left or right.

7 Discussion

The results of this study were threefold. First, the exocentric views provided during the spatial navigation in the virtual multilevel building can significantly improve the accuracy of mental representation of the spatial horizontal information (see Figures 3(a) and 3(b)). This result supported the first hypothesis that the exocentric views facilitate the acquisition of survey knowledge in space [8, 13]. The exocentric views, however, could not significantly facilitate the mental representation of spatial vertical information, which did not support the first hypothesis. The distinct effect of the exocentric view on the mental representations of spatial horizontal and vertical information demonstrated that spatial information on the horizontal and vertical dimensions is represented differently in memory.

Second, compared with the static exocentric views provided by the 3D floor map, the dynamical exocentric views provided during the vertical movement between levels in the transparent condition can better assist subjects to acquire spatial vertical information (see Figures 4(a) and 4(b)). This result did not support the second hypothesis.

Last, the orientation dependent mental representation was observed even though subjects could acquire the exocentric views of the virtual environment (Figure 3(b) and 4(b)). This result supports the third hypothesis. The extra exocentric views provided during the spatial navigation could not ensure the orientation-free mental representation of the virtual multilevel building.

In general, subjects in the transparent conditions perform best in the present experiment. The reason would lie in two aspects. First, compared with the 3D floor map condition, subjects in the transparent condition could acquire more exocentric views of each level. The increased number of exocentric views helped subject better observe the spatial layout. This result was consistent with our previous finding in the virtual room space [5]. Second, the way to provide the exocentric views in the transparent condition was more natural, and subjects would be easy to switch between the egocentric and exocentric views.

The preferred orientation in the mental representation of the virtual room space was aligned with the facing direction (the forward direction) when subjects first enter each level. This finding was consistent with the previous research [9], suggesting that the first view of the environment should be most salient in the spatial memory even though subjects could walk around and faced different directions in the environment.

The findings of the present study have two important implications for assisting spatial navigation in VE. The first implication is that VE designers should provide the continual and better natural exocentric views for users during their navigation in the virtual multilevel building. For example, when users take elevation in the virtual multilevel building, the designers can provide the escalator for users so that users can observe the exocentric views of the spatial layout. The second implication is about the design of the 3D map of building. When a 3D map is employed to assist the navigation in the virtual multilevel building, the 3D map should illustrate the vertical relationship between levels in a multilevel building (also see [2]). The present study has demonstrated that the 3D floor map which only illustrates the spatial layout on one level can impair the mental representation of spatial vertical information among three levels.

Our future work will further investigate the design of the 3D map for navigation in a virtual multilevel building. Some research questions are remained. Besides the requirement of illustration of spatial vertical relations between levels, what are other requirements? What is the effect of the 3D map of building on the wayfinding performance in the virtual multilevel building? Can users improve their wayfinding strategy in the virtual multilevel building if the 3D map is applied?

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