Spatial representation and learning in real and virtual environments

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SPATIAL REPRESENTATION AND LEARNING IN

REAL AND VIRTUAL ENVIRONMENTS

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Abstract

Few things are as fundamental to the human experience as spatial navigation in the real and virtual environments. People navigate in environments by extracting ambience information, forming a mental representation, and in turn employing that mental representation for route planning and maneuvering. Crucial for spatial navigation, mental representation of the environment, namely spatial representation, is the internalized reflection and reconstruction of environment in thought. Meanwhile, the acquisition of accurate and complete mental representations, referred to as spatial learning, is much affected by human's egocentric experience within the environment together with various environment characteristics.

This research aims to understand the cognitive processes of building appropriate mental representations of the environment. In particular, this research investigates the spatial representations acquired in a 3D room environment as well as in a multilevel building. Human egocentric experience is operationalized based on varying exocentric views according to either watching from different exocentric perspectives or learning from 3D maps. Also reckoned are environmental characteristics including the environmental geometry and complexity.

Four studies are conducted systematically to justify hypotheses of spatial representation and learning with respect to different egocentric experiences and environment characteristics. The results reveal that (1) Spatial information on the horizontal and vertical dimensions of the environment is encoded and represented in terms of different frames of reference regarding spatial navigation; (2) The exocentric views associated with an exocentric perspective or a 3D map facilitate the acquisition of survey knowledge, instead of route knowledge, of the environment; and (3) Spatial representation inherently preserves specific biases, regardless of egocentric experiences and environment characteristics.

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Chapter 1 Introduction

1.1 Motivation

Few things are as fundamental to the human experience as spatial navigation in people's daily life. People navigate by extracting information, forming mental representation, and using that mental representation for route planning and moving. In practice, people use whatever the environment gives them to solve navigation problems and continually refine and update the mental representation of the external environment. Spatial navigation in real and virtual environments has been recently received much attention of many researchers across different disciplines (Acta Psychologica, 2005; Bowman, 1999; Golledge, 1999; Presence, 1998, 1999; Shah & Miyake, 2005).

One landmark of this line of research is the emergency of spatial cognition in psychology, which is intended to account for spatial behavior in terms of underlying mechanisms and the associated representations (e.g., Siegel & White, 1975). The increased research about spatial cognition has paralleled the development of behavioral geography, for example, the part of human geography intends to explain how the behavior of individuals within a geographic environment is determined by their cognitive representations (e.g., Downs & Stea, 1973; Moore & Golledge, 1976). Over the same period of time, the connections between psychology and other cognitive sciences, such as linguistics and computer science, have led scientists towards new frontiers in the study of the capacities of human and artificial cognitive systems. For instance, the acquisition and representation of spatial knowledge have become a primary task for computer scientists (e.g., Freksa, Brauer, Habel, & Wender, 2000).

The research about mental representation of the environment is a key part of spatial cognition

since mental representation plays a significant role in successfully navigating in both real and virtual environments. Mental representation is the internalized reflection and reconstruction of environment in thought, including the structure, entities, and relations of environment. It is also called "spatial representation" or "cognitive maps" in literature (Montello, 2005; Lynch, 1960; Siegel & White, 1975; Tolman, 1948). The process to acquire mental representation of the environment is generally called spatial learning. People's mental representation of the environment is easily affected by their learning experiences with the environment and the environmental characteristics. One typical example in daily life is that people live and work in buildings which comprise rooms predominately with rectangular shape, in other words, there are salient orthogonal axes in surrounding rooms. As a result, a preference is observed that people tend to represent objects' locations in memory with respect to orthogonal axes (Shelton & McNamara, 2001; Werner & Schindler, 2004).

Many theoretical models have been proposed to define the way how people build mental representation of the environment in mind (e.g. Allen, 2004). Three models are received much attention in this area. First, the spatial framework (e.g. Bryant & Tversky, 1999; Franklin & Tversky, 1990) suggests that the environment around body is represented with respect to an egocentric reference system comprising three body axes: front / back, right / left, and head / foot. The dominant direction is determined by the interaction between the asymmetries of the body, which are dominated by the front / back axis, and asymmetries of the environment, which are dominated by the up / down axis.

Second, Sholl's model (e.g. Easton & Sholl, 1995; Sholl & Nolin, 1997) contains two subsystems. The self-reference system encodes self-to-objects spatial relations in body-centered coordinates using the body axes of front / back, right / left, and head / foot (the same as the above spatial-framework model). The object-to-object system encodes the spatial relations among objects in environmental coordinates. The two systems interact in several

ways. For example, as the self-reference system changes heading by the way of actual or imagined rotations of body, the orientation of the object-to-object system changes as well.

Finally, McNamara's model (McNamara, 2003; Mou & McNamara, 2002; Shelton & McNamara, 2001) proposes that when people learn a new environment, they interpret the spatial structure of that environment in terms of a spatial reference system which is intrinsic to the spatial structure. Intrinsic directions are selected using various cues in which the dominant cue is the egocentric experience; and the intrinsic reference system selected during the first learning experience is not usually updated as the people move through the environment.

Previous research generally distinguishes route knowledge and survey knowledge, from spatial knowledge development point of view, in the mental representation of the environment (Montello, 2005; Siegel & White, 1975). Route knowledge is the knowledge of sequence of places or landmarks connected by locomotion patterns. Survey knowledge is the knowledge of a layout of places or landmarks and their spatial interrelationships. The "purest" route knowledge and survey knowledge are endpoints on a continuum. One individual's mental representation of the environment includes both route knowledge and survey knowledge at the same time (Burgess, 2006; Sholl, 2001). The rich learning experience, such as navigation in environment or map learning (Darken & Sibert, 1996), can improve the acquisition of survey knowledge in environment.

One key finding in the previous research is that frame of reference (or reference system) plays a key role in spatial representation and learning. Although there are numerous frames of reference, many can be classified as egocentric or exocentric. Egocentric frame of reference is defined with respect to some parts of observer; exocentric frame of reference is external to the holder of the mental representation and independent of his or her position and orientation. Spatial framework suggests that the mental representation of the environment is built with

respect to the egocentric reference (body axes); McNamara's model declares that the mental representation is built with respect to the exocentric reference (the intrinsic reference in environment); In Sholl's model, the mental representation of environment is built with respect to the exocentric reference but this representation is highly influenced by the egocentric reference.

In order to further understand the mental representation of the environment, this research identifies three challenges brought by the previous research.

(1) Three-dimensional property of mental representation. The spatial framework studies the mental representation of the environment surrounding body and points out three-dimensional (3D) property of mental representation. For instance, the mental representations around head / foot, front / back, left / right body axes are not accessed equally. Although the self-reference system in Sholl's model adapts the finding of spatial framework, Sholl and colleagues mainly focused on the representation of spatial relations among self and objects on one plane. McNamara's model also focuses on the spatial structure on one plane. The last two models neglect how people represent the spatial information on the vertical dimension of environment, that is, the spatial verticality information.

In fact, people can identify and remember spatial horizontal and vertical information of environment. Gärling, et al. (1990) provided evidences that the vertical information of buildings in a city plane was observed in memory. Vidal and Berthoz (2005) suggested that the way spatial information is processed and stored depends on whether it relates to the vertical or the horizontal dimension of environment. Studies about the mental representation of the environment indicate that human mind can do 3D spatial process during navigation. The research in weightless environment is one example that crewmembers need accurate 3D mental representation for navigation in a space station (e.g. Oman, Shebilske, Richards, Tubre, Beall, & Natapoff, 2000). Few studies systematically investigate mental representations of

spatial horizontal and vertical information at the same time, and furthermore compare the differences between these mental representations.

(2) Acquisition of survey knowledge in the environment. Previous research points out that spatial learning with the map assistance can facilitate the acquisition of survey knowledge in real and virtual environments (Bronzaft, Dobrow, & O'Hanlon, 1976; Mentello, Hegarty, Richardson, & Waller, 2004; Sholl, 1999; Thorndyke & Hyes-Roth, 1982; Tversky, 1993, 2000; Uttal, 2000). Map provides an overview of the environment and help individual to be aware of his or her position and orientation in the environment. For example, Thorndyke and Hyes-Roth (1982) found that subjects with a building map could better judge the relative location between objects in a building than their counterparts who navigated inside this building.

It should be noted that most maps studied in the previous research only display two-dimensional (2D) spatial information of the environment without the spatial verticality information. 2D map would not be the optimal tool to acquire survey knowledge when spatial verticality information is important for understanding 3D spatial structure of the environment. On the contrary, the 3D map which depicts environment from outside environment and preserves the spatial verticality information is found to be more effective, rather than 2D map, to assist navigation (Fontaine, 2001; Hickox & Wickens, 1999; Wickens & Prevett, 1995). However, there are few studies to investigate the design of a 3D map for facilitating the acquisition of survey knowledge in constrained environments, such as the architecture.

One alternative way to provide the overview of environment is watching from a bird's-eye perspective outside environment (Shelton & McNamara, 2004). The bird's-eye perspective is generally called the exocentric perspective while the perspective within environment is called egocentric perspective. The effect of spatial learning with exocentric perspective on the mental representation of the environment has been rarely investigated although a few studies

are exceptions. In Witmer, Sadowski and Finkelstein (2002) study, when subjects could watch the floor layout from an exocentric perspective, they could acquire a highly evolved state of survey knowledge. More studies are called to investigate the effect of exocentric perspective on the acquisition of survey knowledge in the environment. On research direction is to consider how to efficiently integrate the views acquired from both exocentric and egocentric perspectives (Koh, Wiegand, Garnett, Durlach & Shinn-Cunningham, 1999; Wickens, 2000).

(3) Characteristics of the mental representation of the environment. One general characteristic revealed in the previous research is the orientation-dependent mental representation in mind. Orientation-dependent mental representation means that spatial information in mind can be best accessed from one specific orientation (the preferred orientation). McNamara (2003) pointed out that the preferred orientation is defined by the intrinsic reference system in the environment and will be changed only if the first view is misaligned but a subsequent view is aligned with salient axes in the environment. The change of preferred orientation indicates that the mental representation of the environment can develop as people's spatial learning experience increases in the environment. The preferred orientation mainly reveals the characteristic of mental representation on the horizontal dimension of environment. So what are the characteristic of mental representation on the vertical dimension of environment? Future studies should investigate more characteristics of mental representation on both horizontal and vertical dimensions of the environment.

1.2 Research problems

This research attempted to understand the cognitive process to build mental representation of the environment, with the main focus on responding to above three challenges. A series of four studies investigated the mental representations acquired in the 3D room environment and the multilevel building. The first two studies (Studies 1 and 2) were conducted in the 3D room

environment with two geometries, one rectangular and one cylindrical, while the last two studies (Studies 3 and 4) were conducted in the multilevel building with different degrees of environmental complexity, one simple and one complex.

Study 1 aimed to investigate mental representation of spatial horizontal and vertical information in the 3D room environment when subjects learned from two perspectives, one exocentric and one egocentric. Subjects experienced these two perspectives by two sequences. Study 1 examined the following questions:

(1) Could the orientation–dependent mental representation of the 3D room environment be built after subjects learned the environment from both egocentric and exocentric perspectives?

(2) How did the sequence of experiencing exocentric and egocentric perspectives influence mental representation of spatial horizontal and vertical information in the 3D room environment?

(3) Could the environmental geometry influence the mental representation of spatial horizontal and vertical information in the 3D room environment when two perspectives were provided?

Study 2 aimed to investigate mental representation of spatial horizontal and vertical information in the 3D room environment when subjects learned this environment from multiple perspectives. Subjects experienced these multiple perspectives in two ways. Study 2 examined the following questions:

(1) Could the orientation-free representation of the 3D room environment be built after subjects experienced multiple perspectives?

(2) How did the way of experiencing multiple perspectives influence mental representation of spatial horizontal and vertical information in the 3D room environment?

(3) Could the environmental geometry influence mental representation of spatial horizontal and vertical information in the 3D room environment when multiple perspectives were provided?

The findings of Studies 1 and 2 were expected to reveal the effect of perspective (especially the exocentric perspective) and environmental geometry on the spatial representation and learning.

The last two studies, Studies 3 and 4, were designed to investigate mental representation of spatial horizontal and vertical information in the multilevel building. Specifically, Study 3 was conducted in the grid-like three-level building and subjects navigated in this building with or without the 3D map assistance. Study 3 examined the following questions:

(1) Compared with the mental representation of the 3D room environment, what special characteristics could be observed in the mental representation of the multilevel building?

(2) How did the 3D map influence mental representation of spatial horizontal and vertical information in the multilevel building?

(3) What format of the 3D map was especially useful for acquiring survey knowledge in the multilevel building?

Extending the design in Study 3, Study 4 was conducted in a complex multilevel building (a subway station). Besides examining above three questions in Study 3, Study 4 examined two more questions:

(1) Could the increased environmental complexity influence the function of 3D map on the acquisition of survey knowledge in the complex multilevel building?

(2) Was there any difference between mental representations of real and virtual environments?

The findings from Studies 3 and 4 were expected to reveal the function of 3D map on the acquisition of survey knowledge in the multilevel building. These findings helped to provide suggestions to design the 3D map of the multilevel building.

1.3 Significances

This research has the following theoretical and practical significances:

(1) The understanding about how people acquire survey knowledge during navigation in the multilevel building can help to design building features and guide navigation inside the building, which is particularly useful in public buildings for transportation.

(2) This research systematically investigates different patterns to integrate both exocentric and egocentric perspectives to acquire survey knowledge in the environment, and points out the mechanism to integrate these two perspectives to improve the understanding of spatial layout in the environment.

(3) This research takes the first step to demonstrate that the 3D map can facilitate the acquisition of survey knowledge in the virtual multilevel building. Future studies can apply the findings to design a 3D map for spatial navigation and training in the virtual environment.

(4) The theoretical contribution of present research is to reveal the property of 3D spatial representation and the different representations of spatial horizontal and vertical information in human memory system, and to identify the factors that affect this 3D spatial representation.

1.4 Organization

This thesis is organized with six chapters to record the research process, the findings obtained in each study and the interpretations of the findings, see Figure 1-1.

In this chapter, the motivation, research problems and significances of this research are presented. Chapter 2 introduces the work that has influenced or informed this research. The implications of the previous research to this research are discussed at the last section of Chapter 2.

Chapter 3 provides the design of this research. The hypotheses are examined in following Chapters 4 and 5. Specifically, Chapter 4 reports two studies conducted in two 3D room environments when subjects learned from two and multiple perspectives, respectively; Chapter 5 reports two studies conducted in simple and complex multilevel buildings, respectively. In each of these four studies, an introduction of purpose and hypotheses is presented first, and then the research method and results are described, following which a discussion of findings of each study is made.

Finally, Chapter 6 summarizes the main contributions and limitations of this research and points out possibilities for future work in this area.
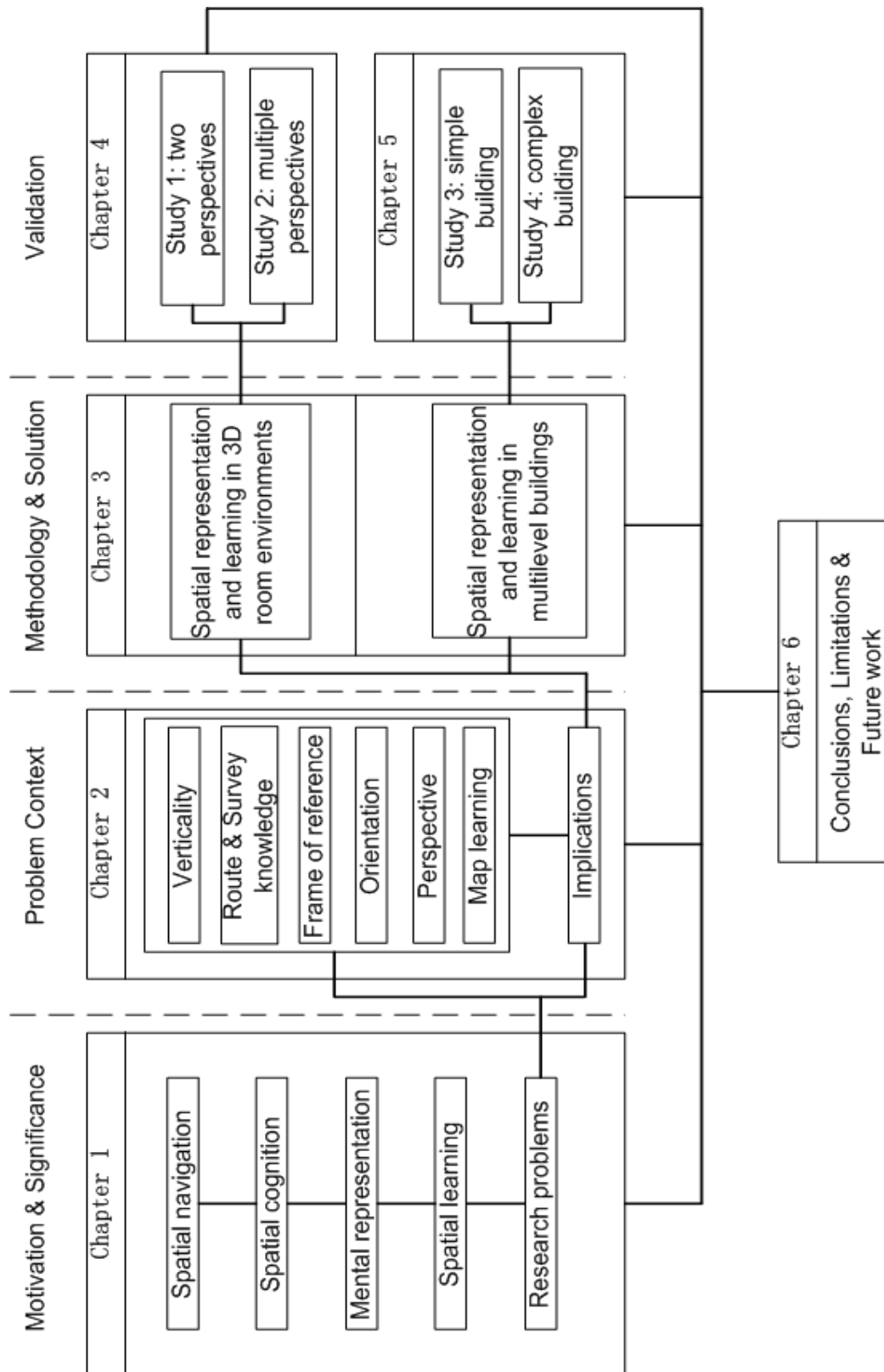
Figure 1-1 Organization of this thesis

Chapter 2 Literature Review

This research has roots in several diverse fields and builds on many previous results. In this chapter, the relevant prior research is introduced. This includes the research about mental representation of the environment, which covers the acquisition of spatial verticality from the environment, structure and bias of the mental representation, and updating of the mental representation. The updating of mental representation needs to acquire spatial information based on different frames of reference, orientations, perspectives, and map learning. The implications brought by the previous research to this research are discussed at the end of this chapter. In particular, the questions raised from the prior research are presented.

2.1 Mental representation of the environment

2.1.1 Mental representation of spatial verticality

Mental representation of spatial verticality is observed in previous research. Gäling, et al. (1990) asked subjects to estimate from memory the difference in elevation between landmarks in the city and found that low precision information on elevation could be retrieved. Their study suggested that the process of verticality in memory is independent of the process of information on the horizontal dimension. In a study conducted in the aligned two-level building, Montello and Pick (1993) used a pointing task to examine the mental representation of two routes, each one on a different level. They found that the pointing performance was slower and less accurate when the reference position and the target position were on different

levels than these two positions were on the same level. A similar finding was also observed in the later study conducted by the first author in the virtual two-level building (Richardson, Montello, & Hegarty, 1999).

More recently, in a study by Wilson, et al.(2004a), subjects explored a symmetrical three-level virtual building with two objects on each level. The results were found that subjects could differentiate objects' positions at different levels in this building. Moreover, the results were found to be more accurate when subject judged the relative position of objects that were located below, rather than above, the horizontal test plane.

2.1.2 Structure of mental representation

The structure of mental representation could be classified into egocentric representation and exocentric representation from the frame of reference point of view (e.g. Burgess, 2006); or be classified into route and survey knowledge from the spatial knowledge development point of view (e.g. Siegel & White, 1975). We will introduce the first type of classification and then the second type of classification, and discuss the relationship between these types of classification.

Egocentric representation means that representation is encoded and stored with respect to the egocentric frame of reference while exocentric representation means that representation is encoded and stored with respect to the exocentric frame of reference. The evidence for the egocentric representation mainly comes from the alignment effect determined by observer's viewing direction. The accuracy or response time advantages are observed when the object

location memory is tested from the viewpoint aligned with the initial one during spatial learning (Rieser, 1989; Shelton & McNamara, 1997). The evidence for the exocentric representation comes from the alignment effect determined by objects in environment. For example, the accuracy or response time advantages are observed when the object location memory is tested from novel viewpoints aligned with the intrinsic of layout (Mou & McNamara, 2002) or salient landmarks in environment (Wener & Schindler, 1999).

Route knowledge and survey knowledge are identified as the two stages of updating mental representation in mind. Route knowledge is knowledge of a sequence of places (or landmarks) connected by locomotion patterns and is typically defined as a mental representation of the procedures necessary for finding one's way from place to place. Survey knowledge is knowledge of a layout of places or landmarks and their direct spatial interrelationships, and is not restricted to spatial interrelationships along routes that have been traveled (Montello, Hegarty, &Richardson, 2004; Siegel & White, 1975). The way of acquiring route and survey knowledge is different: people tend to acquire the route knowledge from navigation inside building while tend to acquire the survey knowledge from map study of building (Thorndake & Hayes-Roth, 1982).

In its purest form, route knowledge is the egocentric representation of environment. In contrast, the purest survey knowledge is the exocentric representation of environment. However, it should be noted that egocentric representation and exocentric representation (or route knowledge and survey knowledge) are not exclusive of each other. Mental representation often combines both the egocentric and exocentric representations at the same time (Burgess, 2006; Sholl, 2001). For example, people may use the egocentric reference to

retrieve the knowledge acquired from the map study (Sholl, 1999).

Route and survey knowledge can be tested from specific spatial tasks. An individual with route knowledge can retrieve the location of landmark but not other objects with less significance along the route he or she navigates in environment. The individual normally struggle to find the alternative route when the learned route is blocked. In contrast, an individual with survey knowledge can perform the following three tasks well. First, significant portions of the spatial layout are memorized allowing for calculation of distances between landmarks and destinations (Euclidean and route). Second, directions to destinations can be indicated accurately. Third, shortcuts can be engineered. Directly requiring subjects to determine the direction and distance to unseen target locations is also an effective method (Siegel, 1981; Witmer & Kline, 1997).

People can acquire both route and survey knowledge after navigating virtual environment. Many studies demonstrate that people can acquire the route knowledge from experience in virtual building (e.g. Ruddle, Payne, & Jones, 1997; Witmer, Bailey, Knerr, & Parsons, 1996). Subjects in the study of Witmer et al. (1996) took routes through three floors of a building and reached six destinations in two office suites. The results suggested that subjects had learned the route well. Very little configuration knowledge was gained from the route-learning experience in VEs.

Some studies suggest that people can also acquire the survey knowledge from experience in virtual building, especially when virtual building depicted is relatively small or simple (Colle & Reid, 1998, 2000; Koh, Wiegand, Garnett, Durlach & Shinn-Cunningham, 1999; Witmer,

Sadowski, & Finkelstein, 2002). Subjects in the study by Koh et al. (1999) learned the floor layout in building through one of four conditions: real world, virtual navigation with HMD, virtual navigation with computer display, and 3D model viewed from a desktop display. Then subjects estimated the bearing and range of various targets in real space from spatially distributed stations. Results obtained from each of the four conditions proved to be roughly the same. The authors suggested that a VE training system that combines an immersive walk-through VE and a miniature-model VE can provide better training to achieve the survey knowledge than real-world training.

2.1.3 Bias of mental representation

Previous research suggests several spatial biases in mental representation of the environment. Three biases received attention in present research, including preferred orientation, vertical same level bias, and downward bias.

First, preferred orientation refers to the spatial relations or characteristics of objects stored in mental representation that are retrieved faster or more accurately from one specifically preferred orientation than from other orientations. The phenomenon demonstrating the bias of preferred orientation is obvious in our daily life. For instance, imagining the world (with our eyes closed) in front of us is easier than imagining it behind us; imagining a space looking forward as we enter it, is easier than imagining it, as we might exit it; recalling the design of spatial layout is more accurate and faster from the direction ever faced in that space than from the novel directions (Shelton & McNamara, 1997). This preferred orientation is determined by egocentric experience, property of environment, experimental instruction, and so on, in

which the egocentric experience plays the critical role (McNamara, 2003). In particular, the preferred orientation bias presents one characteristic of mental representation along the horizontal dimension.

Second, the vertical same level bias is observed in both real and virtual multilevel buildings. In the study conducted in the aligned two-level building, Montello and Pick (1993) used a pointing task to examine the mental representation of two routes on a different level, each with several objects. They found that the pointing performance was slower and less accurate when the target object and the reference object lay on different levels rather than in the same level. According to Richardson, Montello, and Hegarty (1999), the result was caused by the disorientation occurring in the close stairwell.

Third and last, downward bias refers to the superiority of downward over upward spatial representations in mind. Wilson, et al. (2004a) provided evidence to support this bias in spatial memory. Subjects in their study explored a symmetrical three-level virtual building with two objects on each level. The relative positions of objects were judged more accurately and consistently when the target objects were located below, rather than above, the horizontal test plane. The researchers explained that this result revealed the influence of the vertical asymmetry of human body axes and the environment on spatial memory, the core concept in spatial framework (Bryant & Tversky, 1999; Franklin & Tversky, 1990) which will be introduced below.

2.1.4 Updating of mental representation

As people navigate environment, they naturally keep updating their mental representation of

around environment. The updating of mental representation includes the updating of both egocentric and exocentric representations (Mou, McNamara, Valiquette, & Rump, 2004; Sholl, 2001; Vidal, Amorim, & Berthoz, 2004).

Many theoretical models have been proposed to define the mental representation of the environment is built or updated in mind (Allen, 2004). Three models are received much attention in this area. The spatial framework (e.g. Bryant & Tversky, 1999; Franklin & Tversky, 1990) suggests that the space around body is represented with respect to an egocentric reference system comprising three body axes: front / back, right / left, and head / foot. Tversky and colleagues employed the response time to retrieve objects as the index to differentiate the accessibility of body axes. They found that accessibility of the axis depends on the relative salience of the axis in context. For the upright observer, the head / foot axis is most salient because it is aligned with the only asymmetric axis of the world, the axis of gravity. The front / back axis is second because of its asymmetries, and the left / right axis is slowest because it has no essential asymmetries. For the reclining observer, there is no body axis aligned with gravity and the front / back axis is now the most salient.

Sholl's model (e.g. Easton & Sholl, 1995; Sholl & Nolin, 1997) is designed to explain the presentation and retrieval of egocentric spatial relations between an observer and objects in the environment and exocentric spatial relations among objects. The model contains two subsystems. The self-reference system encodes self-to-objects spatial relations in body-centered coordinates using the body axes of front / back, right / left, and head / foot (adapted from above spatial-framework model). The object-to-object system encodes the spatial relations among objects in environmental coordinates. This system is formalized as a

network of nodes, each representing a different object, interconnected by vectors. Spatial relations in this system are specified only with respect to objects in environment. The two systems interact in several ways. For example, as the self-reference system changes heading by way of actual or imagined rotations of body, the orientation of the object-to-object system changes as well.

McNamara's model (McNamara, 2003; Mou & McNamara, 2002; Shelton & McNamara, 2001) comprises four principles: 1) when people learn a new environment, they interpret the spatial structure of that environment in terms of a spatial reference system; 2) the reference systems are intrinsic to the layout; 3) Intrinsic directions or axes are selected using various cues. These cues include the experiences of the observer, properties of the objects, and the structure of the surrounding environment. The dominant cue is egocentric experience because the environment in which human navigate rarely have directions as salient as those established by point of view; 4) the intrinsic reference system selected during the first learning experience is not usually updated with additional views or as the observer moves through the environment. The initial reference system is updated only if the first view is misaligned but a subsequent view is aligned with salient axes in the environment.

These theoretical models demonstrate that when building mental representation of the environment, people need to mentally manipulate spatial information based on different frames of reference, orientations, and perspectives. The result is to acquire more survey knowledge and to build more accurate spatial representation in mind.

2.2 Frame of reference

2.2.1 Egocentric and exocentric references

Frame of reference plays a vital role in processing spatial information in memory. McNamara (2003) pointed out that human mental representation system must use spatial reference systems to preserve the remembered locations of objects. Egocentric and exocentric frames of reference are identified for the purpose of understanding mental representation. An egocentric frame of reference is defined with respect to some part of the observer whereas an exocentric frame of reference is external to the observer. The content of mental representation might be encoded and represented with respect to the egocentric reference (Wang & Spelke, 2002), the exocentric reference, such as the intrinsic axis of layout (Mou & McNamara, 2002; Werner & Schmidt, 1999) and the building wall (Hartley, Trinkler, & Burgess, 2004), or both egocentric and exocentric references (Sholl, 2001; Woodin & Allport, 1998).

One specific frame of reference would be employed to perform one spatial task in daily life. Howard (1993) related the egocentric task, for example the orientation of an object, to the egocentric frame of reference, whereas the exocentric frame of reference supports tasks involving geographical directional judgments. Likewise, Wickens and Hollands (2000) explained that the egocentric frame of reference is suitable for tasks involving navigation and the exocentric frame of reference suits tasks that require an understanding of the position in space.

Environments offer many features that can influence both spatial perception and cognition of

environment structure. Lynch (1960) found that a citizen's mental representation of city is greatly influenced by five key elements: landmarks, paths, nodes, edges, and districts. Main streets and paths give a clear sense of direction and determine the ease with which spatial relations among different places or regions can be understood. Passini (1984) suggested that the architecture has the same five key elements. Good architectural design enables the navigator to extract relevant spatial information for wayfinding or understanding.

2.2.2 Egocentric and exocentric representations

Many researchers have discussed the property of the egocentric and exocentric representations of environment, and the interaction between the two in memory (Burgess, 2006; Mou, McNamara, Valiquette & Rump, 2004; Neggers, Scholvinck, Lubbe & Postma, 2005; Sholl, 2001). First, there is good evidence that spatial information is based on the coordinate system organized around extensions of the three major body axes: head/foot, front/back and left/right, as suggested by the spatial framework (Bryant & Tversky, 1999; Franklin & Tversky, 1990). Experimental data find that spatial information should be more easily accessible if the imagined heading during test coincides with the orientation of the observer (Presson & Hazelrigg, 1984) or with the first viewing direction (Shelton & McNamara, 1997) during spatial learning, which is known as the alignment effect.

Second, the exocentric representations of spatial relations have also been proposed in previous research (McNamara, 2003). Spatial objects and relations are encoded and represented with respect to other objects or the global coordinate systems, independent of the perspective and location of the observer. The alignment effect might be also observed when

the imagined heading during test coincides with the intrinsic axis defined by the environment (Mou & McNamara, 2002; Shelton & McNamara, 2001). Shelton and McNamara (2004) suggested that a principal reference vector in space should first be established for encoding locations while the process of selecting from the large number of possible intrinsic reference systems appears to be driven by the egocentric viewpoints, instructions, or salient environment structures. Alignment effects observed in both the egocentric and exocentric representations are the solid proof to demonstrate the orientation-dependent mental representation of the environment.

It should be noted that the change of environmental geometry and complexity could impact navigation in environment. Sovrano & Vallorigara (2006) found that the spatial orientation mainly relies on the geometric information in the small space while relies on the landmark information in the large space (see also Moeser, 1988). The dependence on the landmark information suggests that the route knowledge is mainly acquired in large space. Weisman (1981) found that subjects felt more difficult to remember and integrate the successive views when the complexity of layout increased.

2.3 Across orientation

In any navigation experience, navigator experiences environment from many different orientations and vantage points. Every turn results in a new orientation; every step results in a new vantage point. The role of orientation in mental representation has been vigorously debated, supporting either orientation-free or orientation-dependent mental representation of the environment. The orientation-free representations means that information can be accessed from the representation equally well from any orientation (e.g. Sholl, 1987); while the orientation-dependent representation means that information can be best accessed from one specific orientation, where this orientation is determined by navigator's experience and environmental characteristics.

The idea of an orientation-free mental representation comes from the need to integrate experiences based on multiple views acquired during navigation. Evans and Pezdek (1980) gave subjects trials of buildings from different viewpoints and asked them to verify the spatial relations among them. Results showed that subjects who learned the building locations through navigation responded equally quickly to all viewpoints. However, the orientation-free representation can not be supported by the mainstream of research. Sholl and Noline (1997) suggest that orientation-free performance is only evidenced under a certain set of conditions and if any one of those conditions is not met, performance will be orientation-dependent. The conditions outlined include a horizontal viewing angle during encoding, a room-sized test space, and "on-path" testing.

Empirical evidence suggests that the orientation-dependent representation can be built with

one view or a limited number of views of environment. Shelton and McNamara (1997) had subjects learn an object array from two views, with the goal of determining whether multiple views would facilitate the construction of an orientation-free representation. Their results suggested that people maintained two orientation-dependent representations – one for each studied view. Furthermore, Diwadkar and McNamara (1997) found that when tested on novel views, subjects needed to reconcile the novel view with the studied view, which led to cognitive difficulty as indicated by response time differences.

While performance appears orientation-dependent with multiple but limited views, the underlying mental representation does not seem necessarily tied to actual viewing orientations. Mou and McNamara (2002) had participants attend to an intrinsic axis within object layout. The intrinsic axis was either congruent with or displaced from the subjects' actual viewing direction. Results showed an orientation-dependent representation tied to the intrinsic rather than the viewing axis.

In further examinations of orientation-free representations, Shelton and McNamara (2001) had subjects learn a layout of objects from one, two, or three viewpoints. The viewpoints were either aligned or not aligned with a salient, environment-defined reference frame, in this case the walls of room. The layout is shown in Figure 2-1. Results indicated that if a viewpoint aligned with the environment reference frame, other actual viewpoints were not as strongly represented. It is important to note that in above studies, the entire spatial array could be viewed from a single vantage point.
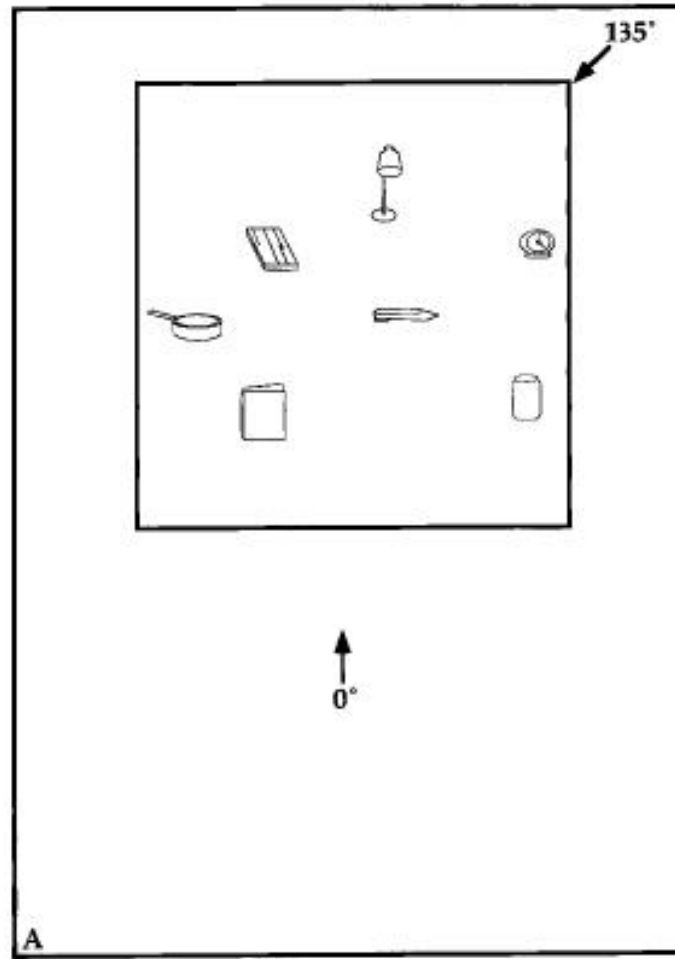
0^0 presents the aligned viewing directions and 135^0 presents the misaligned viewing directions,

adapted from Shelton and McNamara (2001).

Figure 2-1 Schematic of layout and viewing direction

2.4 Across perspective

The navigator within environment normally carries out a process of route learning through the eye-level perspective. Route learning takes advantage in observing the details of spatial objects inside the layout but requires the navigator to dynamically integrate the successive views engaged in environment. The eye-level perspective involved in the route learning is called the egocentric perspective. On the contrary, the navigator in air carries out a process of survey learning through the exocentric perspective external to environment. The properties of the global layout structure, such as the shape of spatial layout, are more easily accessed through the exocentric perspective. Survey learning, however, may lose some spatial information, such as the relative height between objects.

Previous research has investigated mental representation of the environment when people learn from egocentric and exocentric perspectives. Rieser, et al. (1982) found that the exposure to the exocentric view of a spatial configuration can facilitate the development of young children's comprehension of the relations among locations (see also Gauvain & Rogoff, 1986). Subjects in the study by Shelton and McNamara (2004) learned the spatial layout on one floor in a large-scale virtual building environment from either the egocentric perspective or the exocentric perspective. The researchers found that subjects represented the building with respect to the frame of reference that was selected on the first leg of route on the floor.

The exocentric view acquired from exocentric perspective can facilitate the acquisition of survey knowledge of environment. Witmer, Sadowski and Finkelstein (2002) had subjects learn 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. The results indicated 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, Stoakley, Conway, & Pausch, 1995), which can be changed at will simply by rotating or zooming in.

One similar experience of learning spatial layout from exocentric perspective is to study map, the external representation of environment. The effect of map study on building mental representation is introduced below.

2.5 Map learning

2.5.1 Principle of map design

Map learning and navigation produce qualitative and quantitative differences in the mental representation of space (Sholl, 1999; Thorndyke & Hyes-Roth, 1982). Map learning is superior for judgments of relative location and straight-line distances among objects. Learning from navigation is superior for orienting oneself with respect to unseen objects and estimating route distances. But with extensive exposure, the performance superiority of maps over navigation vanishes. People check the map during navigation in the city and building. The use of maps could change the way that spatial knowledge acquired from the navigation is processed in memory (Uttal, 2000).

Maps include symbols of varying size, shape, color, and extent, simplify and regularize information, and use inconsistent scale and perspective (Bronzaft, Dobrow, & O'Hanlon, 1976; Tversky, 1993, 2000). These qualities make the map features subject to attentive and pre-attentive processing. Features close together and similar in form or function are remembered as spatially belonging together. The presence of boundary lines also affects the grouping of map components (Huttenlocher, Hedges, & Duncan, 1991; Rossano & Morrison, 1996). Warren, Rossano, and Wear (1990) found that buildings with visually discriminable subsections were better remembered. Functional color coding leads to similar memory improvement.

There are three major psychological considerations in map design (Levine, Jankovic, & Palij, 1982).

◆ The two-point theorem states that a map reader must be able to relate two points on the map to their corresponding points in the environment in order to determine scale and direction of map.

◆ The alignment principle states that the map should be aligned with the terrain. A line between any two points in space should be parallel to the line between those two points on the map.

◆ The forward-up principle states that the upward direction on a map must always show what is in front of the viewer.

The primary issue of map design is that a map must be congruent with its environment. This allows the map learner to quickly identify his position and orientation on the map and consequently in the environment. The misalignment between map and environment affects map comprehension since mental transformation is required (Aretz & Wickens, 1992). "You-are-here" maps that are misaligned with the environment frequently result in people heading in the wrong direction (Levine, Marchon, & Hanley, 1984).

The forward-up principle actually illustrates the relationship between the map and user, which is regarded as a special alignment by Levine, Jankovic, and Palij (1982). When learning a map from a single orientation, people typically find it easier to make spatial judgments that

are aligned with the familiar orientation by comparison with novel, misaligned views (MacEachren, 1992; Presson, Delange, & Hazelrigg, 1989; Tlauka & Nairn, 2004). This is the "alignment effect" in map study. Furthermore, Tlauka and Nairn (2004) found that alignment effect also exists in the mental representation acquired from learning maps from multiple viewpoints. The alignment effect is commonly assumed to indicate that mental representation of the environment is orientation- dependent.

According to alignment effect, distortions are found in memory for map. Tversky (1981) pointed out that the distortions can be attributed to two cognitive heuristics: alignment and rotation. Alignment heuristic results in a memory distortion where two landmarks are remembered as being more directly horizontally or vertically aligned with one another than they actually are. Rotation heuristic involves rotating a landmark to be more in line with a canonical frame, such as the border of a map or the north-south-east-west coordinate system. Tversky and Schiano (1989) showed that people impose symmetry onto memory for maps. For example, people who were shown curves depicting rivers remembered these curves as more symmetrical than actually depicted. Similarly, an original rectangular shape would be believed to be more of a square.

It should be noted that most maps are two-dimensional (2D) and omit the elevation in the environment while simulating observation of environment through the exocentric perspective that is orthogonal to the ground. The reason might be that elevations are assumed only to provide information about what the structure looks like, which is important for recognition. The lack of elevation information, however, can impair the understanding of spatial structure.

The evidence comes from the benefit of employing three-dimensional (3D) maps or displays for spatial learning.

2.5.2 3D map

3D map is created by using monocular and/or binocular depth or distance cues to create a 3D image (Wickens, 2000). 3D maps can be distinguished by their viewpoints. Egocentric viewpoints depict the world as it would look from the individual within the environment. Exocentric viewpoints show the individual and world from outside, usually from above and behind. A series of studies conducted by Wickens and colleagues found that different 3D maps can influence pilot's performance in spatial task (Hickox & Wickens, 1999; Schreiber, Wickens, Renner, Alton, & Hickox, 1998; Wickens, 2000; Wickens & Prevett, 1995). Generally, the 3D egocentric map is appropriate for local guidance; the 3D exocentric map, especially when the elevated viewpoint is 45^0 angle, enhances the understanding of spatial structure and situation awareness in environment.

In buildings, Fontaine (2001) investigated the role of the 3D map in understanding building structure. The author compared the effect of floorplans, floorplans associated with a frontal map, and a 3D exocentric map (depicting the station from a viewpoint external to the station and through the perspective oblique to the station) on learning the layout of subway station. The result showed that subjects with the 3D exocentric view could better elaborate a correct mental representation of the vertical relations between levels of the station.

While 3D displays have been advocated due to their natural, integrated representation of the 3D world, costs in terms of spatial awareness biases and distortions are inherent. One of these biases is the "2D-3D effect" which leads users to subjectively rotate vectors in depth more parallel to the viewing plane (McGreevy & Ellis, 1986). This effect may manifest as biases in three related ways. First, the slant underestimation effect causes viewers to perceive the slanted surface shorter and more parallel to the viewing screen than it actually is. Wickens (2002) points out that accurate perception of the true orientation of a slanted surface in depth requires cognitive integration of all existing depth cues. Second, the compression effect is a spawned cost of portraying a 3D world on a 2D screen (Boeckman & Wickens, 2001). An increase in the amount of compression of an axis is coupled with a reduction in resolution of position along that axis to the extent that the viewing plane or vector approaches an angle parallel to the line-of-sight. Third, the line-of-sight ambiguity effect reduces the amount of linear information available within a visible vector as that vector approaches the line-of-sight viewing axis.

Wickens, Vincow, and Yeh (2005) pointed out that the critical factor in designing different 2D or 3D maps is the frame of reference. Any representation of environment must define at least two frames of reference: an egocentric frame representing the momentary location and orientation of the user, and an exocentric frame in which the environment is represented. Meanwhile, the task required of the user requires varying kinds of transformations among reference frames. These transformations in turn vary in their difficulty, which account for the error and the delay in the spatial task (Wickens, 1999).

2.6 Summary and Implications

Previous research provides theoretical and empirical foundations to the future research. This research focuses on four major implications of the previous research.

2.6.1 Horizontal and vertical mental representations

Previous research suggests that people can represent spatial information on both horizontal and vertical dimensions of the environment. Gäling, et al. (1990) pointed out that the spatial process of information on the vertical dimension is independent of the process of information on the horizontal dimension. Furthermore, the spatial framework (Bryant & Tversky, 1999; Franklin & Tversky, 1990) explored the mental representation along three body axes: front / back, right / left, and head / foot and revealed that mental representations along these three axes are not equal with each other. These findings indicated that (1) mental representation of the environment is three dimensional (3D), including both the horizontal and vertical mental representations; (2) when investigating mental representation of the environment, researchers should identify the dimension of environment the spatial information relates to.

One research question is raised: why are the mental representations on the horizontal and vertical dimensions different? Spatial framework explains this difference in terms of the interaction between the egocentric reference (the body axis) and the exocentric reference (the gravity). In other words, the two mental representations are encoded and represented with respect to different frames of reference. This research further examines the function of frame of reference on building mental representation. In particular, the egocentric reference

considered in the present research is the perspective from which subjects learn the spatial layout of environment, while the exocentric reference includes the environmental geometry and objects of spatial layout.

2.6.2 Spatial learning from the exocentric perspective

Previous research suggests that the exocentric view acquired from the exocentric perspective can facilitate the acquisition of survey knowledge in the environment (Koh, et al, 1999). The reason is that the exocentric frame of reference is easy to be employed in the exocentric view. However, the effect of exocentric view on the mental representation has not been systematically investigated. One lack of research is the spatial learning from both egocentric and exocentric perspectives. In particular, less attention is paid to the way in which the egocentric and exocentric perspectives could be effectively integrated. For example, subjects in study by Witmer, Sadowski and Finkelstein (2002) pressed one key to activate the exocentric view displayed on HMD and then pressed another key to go back to the egocentric view.

Two questions are addressed: (1) what is the property of mental representation of the environment when people learn the environment from both egocentric and exocentric perspectives? (2) Does spatial learning from both egocentric and exocentric perspectives facilitate the acquisition of survey knowledge in the environment?

2.6.3 Spatial learning with the 3D map

Previous research suggests that spatial learning with the 3D map assistance can also facilitate the acquisition of survey knowledge in the environment (Fontaine, 2001; Wickens, Vincow, &Yeh, 2005). Durlach, et al. (2001) pointed out that "going back and forth easily and quickly between exocentric views of maps and models of spaces and egocentric views derived from being in the space (real or virtual) can serve as a powerful tool not only for remaining oriented in complex space, but for 'truly learning the space'" (p. 599). The use of 3D map to assist spatial learning, however, has not been seriously investigated. In particular, the use of 3D map to assist navigation in buildings–the constrained 3D environment–has not received much attention. Fontaine (2001) points out that, compared with the 2D floor layout map, the 3D map illustrating the vertical relations between levels facilitates the understanding of spatial structure in a multilevel building (a subway station). This research takes a further step in order to answer the following two questions: (1) Does the 3D map facilitate the acquisition of survey knowledge in the multilevel building; (2) If true, what are the requirements to design a 3D map of the multilevel building?

2.6.4 Property of mental representation

Previous research suggests that there are biases in the mental representation of the environment. For instance, the orientation-dependent mental representation, which reflects the bias of mental representation of spatial information on the horizontal dimension of environment, is generally observed in the previous research, even after people could observe spatial layout from multiple (limited numbers) views (e.g. Shelton & McNamara, 2001). Besides the orientation-dependent bias, the vertical same level bias and the downward bias,

which reflects the bias of mental representation of spatial information on the vertical dimension of environment, are also observed in the previous research. It should be noted that much research investigates these biases when subjects learn spatial layout from the egocentric perspective. Less research investigated these biases when subjects learned spatial layout from the exocentric perspective.

As introduced above, the exocentric view acquired from exocentric perspective can facilitate the acquisition of survey knowledge. This research investigates the effect of the exocentric view on influencing these biases. Two research questions are raised: (1) Will the spatial biases exist when the environment is learned from both egocentric and exocentric perspectives? (2) Will the spatial biases exist when people are assisted by the 3D map during spatial leaning?

In the following Chapter 3, we will introduce the general design of this research. The detailed case studies have been conducted to verify our design. The case studies are presented in Chapters 4 and 5.

Chapter 3 Spatial Representation and Learning in Environments

This chapter describes the overall design of this research. Four studies would be conducted in the virtual environment (VE) while one experiment of the forth study would be conducted in the real environment.

VE technology has been demonstrated to be an effective research tool to study spatial cognition in reality (Loomis, Blascovich, & Beall, 1999). Navigation in VE and the real world share many similarities. Many studies find that people can acquire route knowledge from the navigational experience in VE (e.g. Ruddle, Payne, & Jones, 1997; Witmer, Bailey, Knerr, & Parsons, 1996). Some studies find that the acquisition of survey knowledge is also possible in VE (e.g. Colle & Reid, 1998, 2000; Koh, Wiegand, Garnett, Durlach & Shinn-Cunningham, 1999; Witmer, Sadowski, & Finkelstein, 2002).

The design of this research is illustrated in Figure 3-1. As introduced in the above two chapters (e.g. section 1.1 of Chapter 1 and section 2.2 of Chapter 2), frame of reference plays a key role in building mental representation of the environment. To answer the research problems raised from the previous research (see section 2.6 in Chapter 2), this research investigated the effects of egocentric learning experiences and environmental (exocentric) characteristics on spatial representation and learning in environments. In particular, the first two studies, Studies 1 and 2, investigated the effect of the perspective and environmental

geometry on mental representation of spatial horizontal and vertical information in the 3D room environment. The last two studies, Studies 3 and 4, investigated the effect of the spatial learning with 3D maps and the environmental complexity on mental representation of spatial horizontal and vertical information in the multilevel building. The mental representation of the environment was examined by the judgment of relative direction (JRD) task. Specifically, the error of judging horizontal angle was used to examine the accuracy of mental representation of spatial horizontal information; the error of judging vertical angle was used to examine the accuracy of mental representation of spatial vertical information. Response time to perform JRD task was also one important criterion to examine mental representation of the environment.
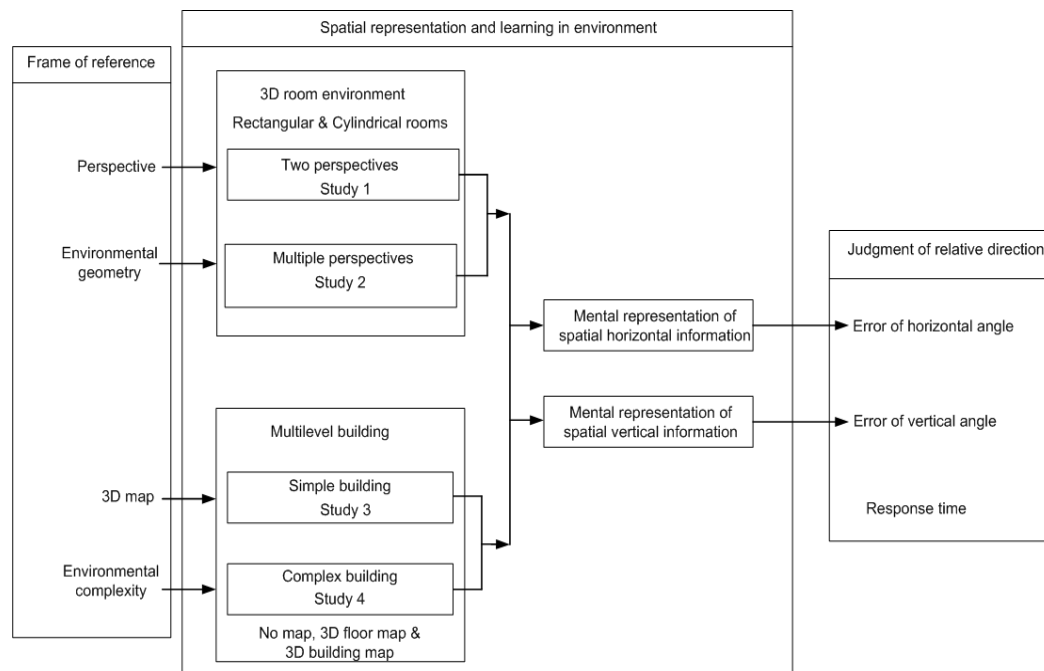
Figure 3-1 Research design for probing spatial learning and representation.

3.1 Spatial representation and learning in 3D room environments

Subjects in Studies 1 and 2 learned spatial layout in 3D room environments from both exocentric and egocentric perspectives. Subjects elevated along the vertical dimension of the room space to experience these perspectives. There were two elevation patterns: discrete elevation in Study 1 and continuous elevation in Study 2. Thus, subjects in Study 1 learned spatial layout only from two perspectives, while subjects in Study 2 learned spatial layout from multiple perspectives. The elevation patterns are presented below, see Figure 3-2 and Figure 3-3.

Furthermore, we investigated the effect of environmental geometry (one typical exocentric frame of reference) on the mental representation of a 3D room environment. Environmental geometry is observed to play a vital role in building mental representation of the small-scale space (e.g. Sovrano & Vallorigara, 2006). Two rooms with different geometries, one rectangular and one cylindrical, were simulated in this research. The main difference between these two geometries was that the rectangular shape includes ecologically valid features, such as the linear shape and the orthogonal angle created by two connected walls, while the cylindrical shape lacked these ecologically valid features. Colle and Reid (2003) found that these ecologically valid features helped their subjects to remember objects' locations in VE.

3.1.1 Study 1: learning from two perspectives

The two perspectives considered in Study 1 included one egocentric perspective with 0^0 elevation angle and one exocentric perspective with 45^0 elevation angle. The selection of 45^0 exocentric perspective was based on findings in the previous research (Hickox & Wickens, 1999; Luo & Duh, 2006; Wickens & Prevett, 1995). For instance, Wickens and colleagues found that when pilots who are assisted by the 3D display navigate a natural environment, the 3D display rendered from the elevated viewpoint with 45^0 angle best enhances understanding of spatial structure and keeps situation awareness in the environment (e.g. Wickens, 1999). Therefore, subjects in this study learned two views of the 3D room environment: the egocentric view acquired from the egocentric perspective and the exocentric view acquired from the exocentric perspective. The sequence to learn these two views was counterbalanced.

Study 1 aimed to investigate the mental representation of spatial horizontal and vertical information in the 3D room environment when subjects learned the room-sized environment from above two perspectives. The study answered three research questions: (1) Could the orientation-dependent representation of the 3D room environment be built after subjects learned the environment from both exocentric and egocentric perspectives? (2) How did the sequence of experiencing exocentric and egocentric perspectives influence the mental representation of spatial horizontal and vertical information in the 3D room environment? (3) Could the environmental geometry influence mental representation of spatial horizontal and vertical information in the 3D room environment when two perspectives were provided?

To answer these three questions, three hypotheses were tested in this study. First, it was hypothesized that the orientation-dependent representation would be built after subjects learned the spatial layout from two perspectives. Second, the sequence of experiencing the 45^0 exocentric and the egocentric perspectives could not influence the mental representation. Third, subjects in the rectangular room would represent spatial layout more accurately than their counterparts in the cylindrical room. The rationale for proposing these hypotheses is presented in the first section of Chapter 4.

In Study 1, the independent variables included two between-subjects variables and one within-subject variable. The first between-subjects variable was the sequence of experiencing exocentric and egocentric perspectives and the second between-subjects variable was the environmental geometry with two levels (rectangular and cylindrical). In particular, the sequence of experiencing exocentric and egocentric perspectives included two types, the exocentric-first condition and the egocentric-first condition, see Figure 3-2. In the exocentric-first condition, subjects first learned the exocentric view acquired from the exocentric perspective and then the egocentric view acquired from the egocentric perspectives; while in the egocentric-first condition, subjects first learned the egocentric view and then the exocentric view.
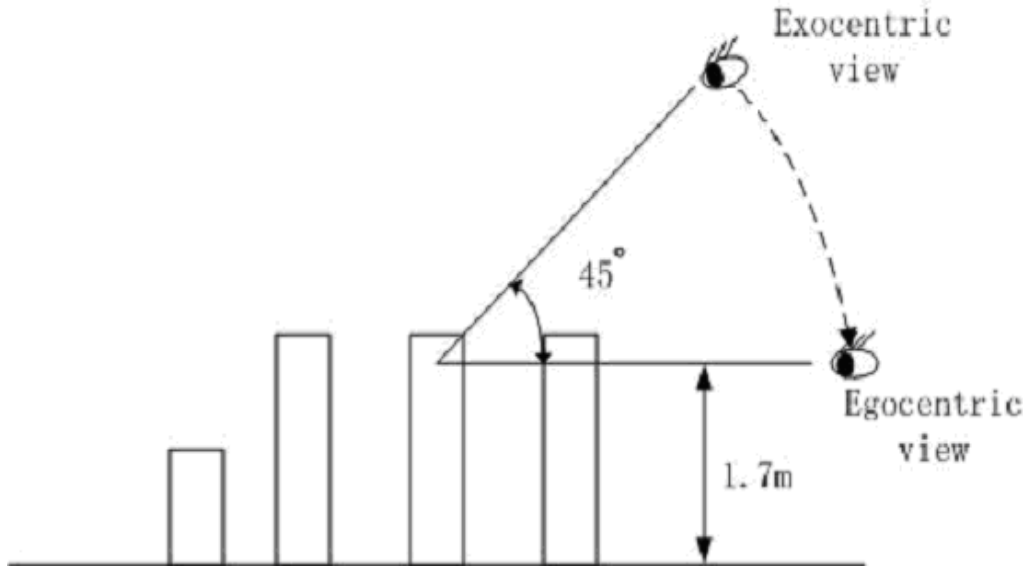
(a) Exocentric-first condition: subjects first learned the exocentric view and then the egocentric view. The dashed line presents the discrete elevation from exocentric perspective and egocentric perspective.
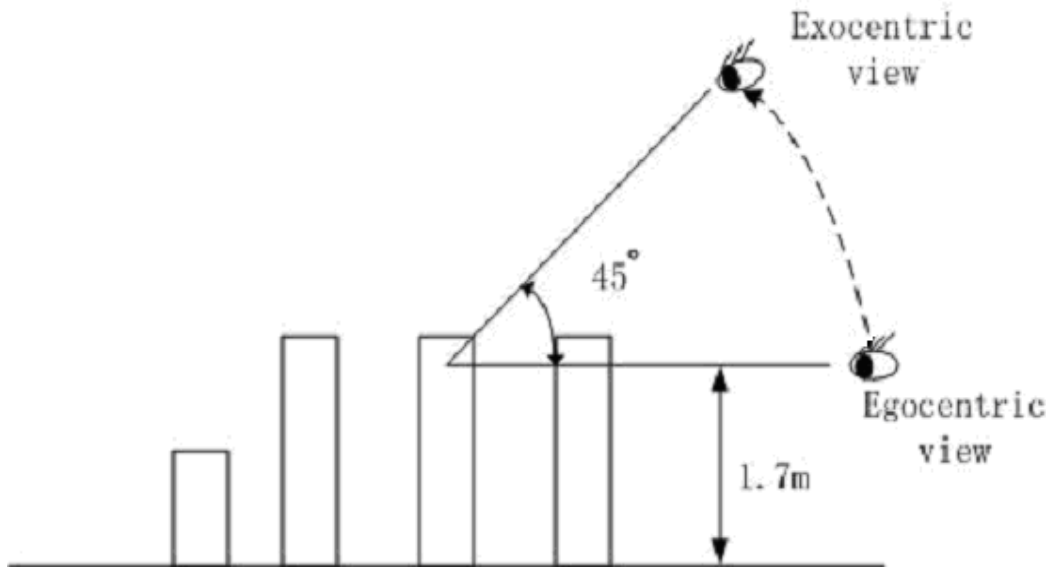
(b) Egocentric-first condition: subjects first learned the egocentric view and then the exocentric view. The dashed line presents the discrete elevation from egocentric perspective to exocentric perspective.

Figure 3-2 The two sequences of experiencing exocentric and egocentric perspectives.

The within-subject variable, the imagined facing direction, defined the characteristic of questions in the judgment of relative direction (JRD, "Imagine you are standing at object A and facing object B, point to object C") task. To perform the JRD task successfully, subjects needed to retrieve the object-to-object relationship in memory with respect to the exocentric reference (Easton & Sholl, 1995). Therefore, JRD examined the survey knowledge (exocentric representation) in memory. Specifically, the imagined facing direction defined from object "A" to object "B" in the 3D room environment could be forward (toward the front wall subjects faced during spatial learning), left/right (toward the side wall), and backward (opposite to forward direction, toward subject's position).

In the JRD task, 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, which examined the accuracies of mental representations of spatial information on the horizontal and vertical dimensions of the 3D room environment, respectively. The reason to measure these two angular errors was to explore the property of mental representation of spatial horizontal and vertical information in this environment. The response time was measured as the time from the presentation of the instruction to the end of subject's response.

All dependent measures were subjected to analysis of variance (ANOVA) in terms of the sequence of experiencing perspectives, environmental geometry and imagined facing direction. A significance level $< .05$ was adopted for all these analyses.

3.1.2 Study 2: learning from multiple perspectives

Subjects in Study 2 learned spatial layout in the 3D room environment from multiple perspectives. The multiple perspectives were driven by the continuous elevation change in the 3D room environment. The continuous elevation change was activated by pressing the arrow key on keyboard to simulate the downward movement in the virtual room. Subjects could watch the spatial layout during the process of continuous elevation change from the 45^0 exocentric perspective to the egocentric perspective.

In particular, the continuous elevation change from the 45^0 exocentric perspective to the egocentric perspective was controlled in two ways in which the eyesights in the 3D room environment were different. In one way, called **attentive elevation**, the eyesight was guided to look at the center of spatial layout during elevation; while in another way, called **normal elevation**, the eyesight was guided to look at the front wall during elevation, see Figure 3-3. The difference between these two elevation ways was that subjects in the attentive-elevation condition could acquire more views of spatial layout than their counterparts in the normal-elevation condition. The reason was that spatial layout on the ground appeared in subject's field of view during the whole process of attentive elevation; while during the process of normal elevation, spatial layout on the ground did not appear in subject's field of view at the beginning of elevation but appeared gradually in the field of view as subject's viewpoint was close to the ground. Hughes and Lewis (2005) found that the more views to target objects during navigation (called the attentive navigation in their study) improved the object recognition, developing an understanding of the configuration of objects, and better

searching for target objects.

Study 2 aimed to investigate the mental representation of spatial horizontal and vertical information in the 3D room environment when subjects learned this environment from multiple perspectives. Three questions were answered in this study: (1) Could the orientation-free representation of 3D room environment be built after subjects experienced multiple perspectives? (2) How did the way of experiencing multiple perspectives influence the mental representation of spatial horizontal and vertical information in the 3D room environment? (3) Could the environmental geometry influence the mental representation of spatial horizontal and vertical information in the 3D room environment when multiple perspectives were provided?

Three hypotheses were tested in this study. The first hypothesis was that the orientation-free representation would be built after subjects learned the spatial layout from multiple perspectives. The second hypothesis was that subjects in the attentive-elevation condition would acquire more accurate mental representation than their counterparts in the normal-elevation condition. Third, subjects could represent spatial layout equally well in the rectangular and cylindrical rooms; that is, there was no effect of the environmental geometry on the mental representation.

In Study 2, the independent variables included two between-subjects variables and one within-subject variable. The first between-subjects variable was the elevation way with two

levels (attentive elevation and normal elevation). The second between-subjects variable was, again, the environmental geometry with two levels (rectangular and cylindrical). The two elevation ways were illustrated in Figure 3.3. In both ways, subjects changed elevation continuously (the downward movement) from the viewpoint of the exocentric (45^0) perspective to the viewpoint of the egocentric (0^0) perspective. By the attentive elevation, the subject's eyesight was adjusted automatically by the system to look at the center of layout at the 1.7 meter height from the ground during elevation. By the normal elevation, the subject's eyesight was adjusted to look at the wall in front of subjects during elevation.

The mental representation was examined again by the JRD task. Thus, the within-subjects variable was the imagined facing direction defined by the question in the JRD task. The dependent variables included the error of horizontal angle, the error of vertical angle and the response time to judge the direction.

All dependent measures were subjected to analysis of variance (ANOVA) in terms of the elevation way, environmental geometry and imagined facing direction. A significance level < .05 was adopted for all these analyses.
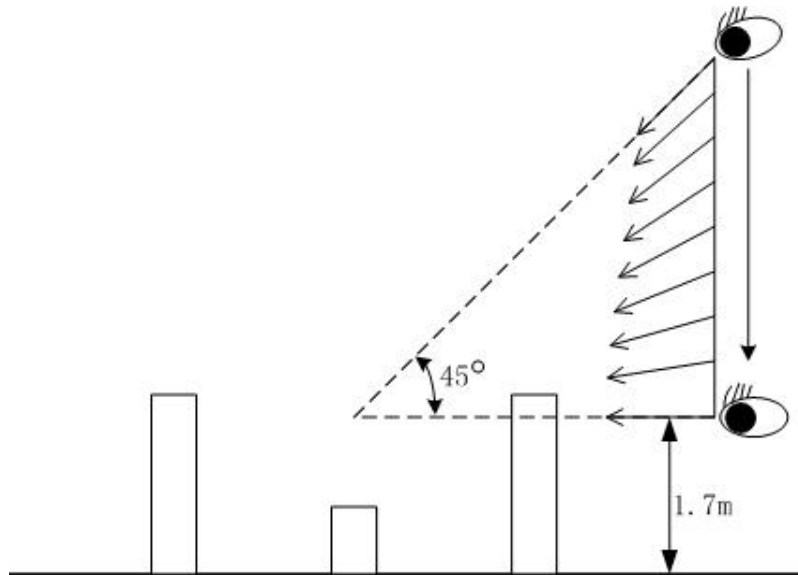
(a) Attentive elevation. The eyesight always watches at the center of layout at the height of

egocentric perspective during elevation
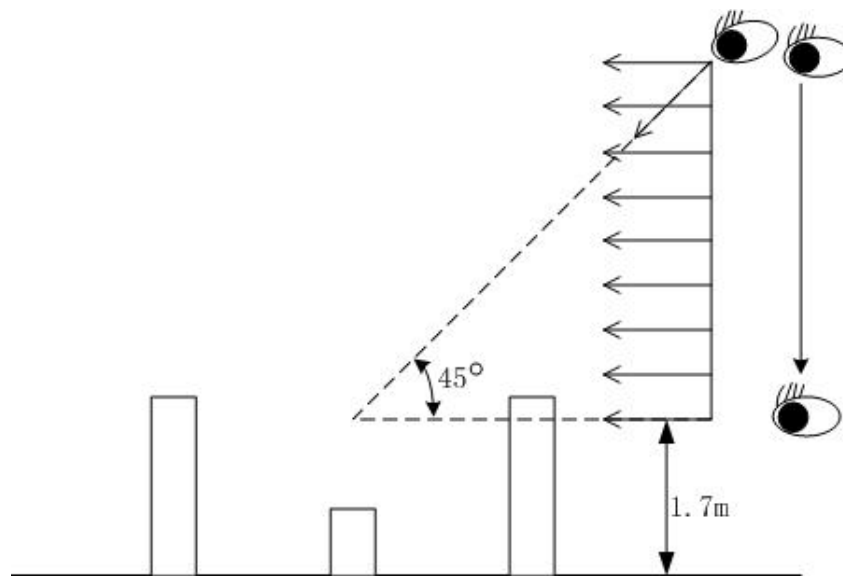
(b) Normal elevation: The eyesight first watches at the center of layout at the height of

egocentric perspective and then watch forward during elevation.

Figure 3-3 Two elevation ways: (a) attentive elevation; (b) normal elevation.

3.2 Spatial representation and learning in multilevel buildings

The mental representation acquired from the navigation in the multilevel building should be more complex than the mental representation acquired from the elevation in the 3D room environment in Studies 1 and 2. It is because people can have more navigational experiences in the multilevel building than in the 3D room environment and also the environmental geometry and structure were more complex in the multilevel building than those in the 3D room environment.

Previous research points out several biases of mental representation acquired from navigation in buildings. Three of them are the focal point in this research. First, the vertical same level bias has been observed in both real and virtual multilevel buildings (Montello & Pick, 1993; Richardson, Montello, & Hegarty, 1999): people can remember the locations of spatial objects more accurately when all objects are on the same level rather than on different levels. Second, the downward bias refers to the superiority of downward over upward spatial representations in mind (e.g. Wilson, Foreman, Stanton, & Duffy, 2004). Third, the preferred orientation refers to the idea that spatial relations or characteristics of objects stored in the mental representation are retrieved faster or more accurately from one specifically preferred orientation than from others (McNamara, 2003; Shelton & McNamara, 1997).

These three biases indicate that although people possess the cognitive ability for 3D spatial

processing, they need external navigational supports to counteract these biases and thus assist their understanding of the multilevel building. A navigational assistance tool, the 3D map, has received much attention from researchers since it can aid pilot's navigation in the 3D natural environment (e.g. Wickens, Vincow & Yeh, 2005) and improve the understanding of verticality in the multilevel building (e.g. Fontaine, 2001). However, the use of 3D maps to assist navigation and spatial learning in environments has not been seriously investigated (Durlach, et. al, 2001). Especially, there is a lack of research to define the guidelines to design a 3D map for navigation in the multilevel building.

A key concept in designing the 3D map is the distinction between the route and survey knowledge – a distinction closely corresponding to the egocentric and exocentric representations of the environment (Montello, Hegarty, & Richardson, 2004; Siegel & White, 1975; see details in section 2.1.2 of Chapter 2). People tend to acquire the survey knowledge from learning the map of building while they tend to acquire the route knowledge from navigation inside the building (Thorndake & Hayes-Roth, 1982). Therefore, the 3D map should facilitate the acquisition of survey knowledge in the multilevel building.

The following two studies, Studies 3 and 4, investigated the mental representation of spatial horizontal and vertical information in the multilevel building, focusing on testing the above three biases of mental representation and the function of a 3D map on the acquisition of survey knowledge in the multilevel building.

We were aware that the benefit of the 3D map to facilitate the acquisition of survey knowledge would depend on the degree of environmental complexity. Previous research finds that when the environment is relatively complex and large, people tend to acquire route knowledge (e.g. Moeser, 1988; Sovrano & Vallorigara, 2006). To completely examine the function of the 3D map on the acquisition of survey knowledge, we built two types of multilevel building: the vertically aligned grid-like three-level building (called the simple multilevel building) in Study 3 and the simulated subway station (called the complex multilevel building) in Study 4.

The subway station in Study 4 is more complex than the grid-like building in Study 3 in fourfold. First, the building size is of the subway station much larger than that of the grid-like building. The maximum length of station was eight times longer than that of the grid-like building. Second, the level geometry of the subway station was irregular while the level geometry of the grid-like building was rectangular. Third, the number of spatial objects in the subway station was much more than that in the grid-like building. Finally, the spatial structure of subway station, especially the vertical structure connecting each level, was more complex than that in the grid-like building. Each level of the subway station was connected by escalators, staircases and one lift, while each level of the grid-like building was only connected by one lift. Therefore, subjects in the subway station were supposed to be more difficult to acquire spatial knowledge than their counterparts in the grid-like building.

3.2.1 Study 3: learning in a simple multilevel building

Study 3 was designed to investigate the mental representation of a simple multilevel building and the function of 3D map on the acquisition of survey knowledge in this building. Three questions were addressed in this study: (1) Compared with the mental representation of the 3D room environment, what special characteristics could be observed in the mental representation of the multilevel building? (2) How did the 3D map influence the mental representation of spatial horizontal and vertical information in the multilevel building? (3) What format of the 3D map was useful for acquiring survey knowledge in the multilevel building?

In this study, the simple multilevel building was augmented with either a 3D floor map, a 3D building map, or neither, where the 3D floor map illustrated the 3D spatial layout on each floor while the 3D building map illustrated the 3D spatial layout across all floors into one rendering. Subjects were required to remember the locations of spatial objects during navigation in the simple multilevel building. In order to measure survey knowledge acquired by navigation, subjects were asked to perform the judgments of relative directions (JRD) task, the same task employed in Studies 1 and 2 (see section 3.1.1).

Three hypotheses were tested in this study. First, the three biases of mental representation discussed above (at the beginning of section 3.2) would be observed after subjects navigated in the multilevel building without any map aid. Second, the 3D map could overcome some or

even all these three biases of mental representation. In other words, compared with subjects without the map aid, subjects with the 3D map aid would acquire more accurate mental representation of the same multilevel building. Third, in comparison with the 3D floor map, the 3D building map could better facilitate the acquisition of survey knowledge since the latter illustrated additional vertical relationships between levels (Fontaine, 2001).

In Study 3, the multilevel building was simulated on the computer and comprised three vertically aligned rooms, one room on each level. There were three objects in each room. There was an elevator aligned with one side wall of the building so that subjects could elevate between levels by taking the elevator. The translation in each room was activated by pressing the arrow keys on the keyboard. Subjects were required to enter each room at least twice and to touch all objects in each room by clicking the mouse.

The independent variables of this study included one between-subjects variable and two within-subject variables. The between-subjects variable defined four kinds of navigation treatment: no map, 3D floor map, and 3D building map and transparent conditions. Subjects were randomly assigned to each of four experimental conditions. The no map group was the control group, in which subjects explored the virtual building without any aid. In the 3D floor map and 3D building map conditions, the 3D map was always displayed in the up-left corner within subject's egocentric view. This method was based on the split-screen technique used in the design of aviation display (e.g., Olmos, Wickens & Chudy, 2000). This design allows subjects to go back and forth easily and quickly between exocentric views of maps of the

environment and egocentric views derived from being in that environment, which is effective for remaining oriented and learning environment (Durlach, et. al, 2001). Lastly, 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. It was designed to provide multiple views of spatial layout on the coming / leaving level, which was, to some degree, similar to the situation in the normal-elevation condition in Study 2.

The two within-subjects variables defined the characteristics of questions in the judgment of relative direction task (JRD, "Imagine you are standing at object A and facing object B, point to object C"): (1) the imagined facing direction from Object A to Object B, the same variable introduced in Study 1; (2) the level difference between the target objects C and the reference objects A and B. 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. 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 memory. The level difference was not considered in Studies 1 and 2 since all objects in the 3D room environment were on the same level – the ground of room.

As introduced in Study 1, the dependent variables in the JRD task were angular error and response time. 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.

All dependent measures were subjected to analysis of variance (ANOVA) in terms of

navigation treatment, level difference and imagined facing direction. A significance level

< .05 was adopted for all these analyses.

3.2.2 Study 4: learning in a complex multilevel building

Subjects in Study 4 navigated a relatively complex multilevel building. In particular, this complex multilevel building simulated a subway station in the downtown of Singapore. This study was designed to response one main concern raised in Study 3: the "elegant" design of experimental building with the simple geometry and layout. Because of this "elegant" design, subjects without the map aid might acquire the same survey knowledge as their counterparts with the 3D map aid. It was possible that the 3D map would take a more significant role in influencing the mental representation of the complex multilevel building rather than the mental representation of the simple multilevel building.

Furthermore, in this study, the mental representations acquired from navigation in the virtual environment (the virtual subway station) were compared with that acquired from navigation in the corresponded real environment (the real subway station). Partly due to the difference of the environmental complexity, no consensus has been reached in the previous research in terms of the spatial learning in real vs. virtual environments. When the environment is relatively simple, like only one floor layout, no significant difference is found between the spatial representations acquired from the real and virtual environments (e.g. Koh, Wiegand, Garnett, Durlach, & Shinn-Cunningham, 1999); however, when the environment is relatively complex, like the two-floor layout, spatial representation tends to be better in the real environment than in the virtual environment (e.g. Richardsonk, Montello, & Hegarty, 1999). In the complex multilevel building in the present study, therefore, it was expected that

subjects in the real environment would acquire better mental representation than their counterparts in the virtual environment.

The purpose of Study 4 was to investigate the mental representation of the complex multilevel building and the function of 3D map on the acquisition of survey knowledge in this complex multilevel building. Besides testing the same three hypotheses in Study 3, we further tested two more hypotheses in the present study. First, we assumed that the 3D map would show a greater benefit to spatial learning in the complex multilevel building than in the simple multilevel building. Second, subjects navigating in the real environment would acquire more accurate mental representation than their counterparts navigating in the virtual environment without map aid, but they would acquire as good spatial knowledge as those in the virtual environment augmented with 3D map aids.

In Study 4, the complex multilevel building (the subway station) comprises three levels: the platform, the middle level and the upper level. Several escalators and staircases connected each level. The shape and size of each level are different. Several facilities were chosen as landmarks in this station. Subjects were required to remember the locations of these facilities when navigating in this station.

The independent variables of this study included one between-subjects variable and two within-subject variables. The between-subjects variable defined four kinds of navigation treatment: no map, 3D floor map, and 3D building map and real-environment conditions. The

two within-subjects variables (the level difference and the imagined facing direction) were the same as those in Study 3. After navigation, subject's mental representation of this building was also measured by the JRD task. The dependent variables were the horizontal and vertical angular errors and the response time, the same as in Study 3.

All dependent measures were subjected to analysis of variance (ANOVA) in terms of the navigation treatment, level difference and imagined facing direction. A significance level < .05 was adopted for all these analyses.

Chapter 4 Spatial Representation and Learning in 3D Room Environments

The main purpose of two studies reported in this chapter is to investigate the mental representation of spatial horizontal and vertical information in the 3D room environment. We focused on the effects of the perspective and the environmental geometry on this mental representation.

The 45^0 exocentric perspective and the egocentric perspective. Previous research recommends that the 45^0 exocentric perspective is the optimal perspective for maintaining the situation awareness in the environment (e.g. Wickens, 1999; Wickens & Prevett, 1995). Egocentric perspective is optimal for learning the details of object for recognition (e.g. Riser, 1989) and for judging the relative direction between a navigator and objects (Thorndyke & Hyes-Roth, 1982).

Orientation-dependent mental representation. As the number of perspective increases in the environment, people can observe the environment from many different orientations and vantage points, which facilitates to building the orientation-free mental representation (Sholl, 1987). To build the orientation-free mental representation, however, is not easy even though people can learn the spatial layout from two or three viewpoints on the horizontal dimension of the environment (Shelton & McNamara, 2001).

The rectangular and cylindrical geometries. The environmental geometry can take function

as one exocentric frame of reference to influence the mental representation of the environment. Compared with the cylindrical geometry, the rectangular geometry preserves ecologically valid features, such as the linear shape and the orthogonal angle created by two connected walls. The existence of ecologically valid features could help people to remember the object's location in the virtual building (Colle & Reid, 2003).

4.1 Spatial representation and learning from two perspectives

4.1.1 Purpose and hypotheses

Study 1 investigated the mental representation of spatial horizontal and vertical information in the 3D room environment with focus on the effect of spatial learning from two perspectives and environmental geometry on this mental representation.

The sequence of experiencing two perspectives. Shelton and McNamara (2001) found that the way of experiencing two viewpoints in the environment could lead to the different cognitive processes in memory. In their study, one viewpoint (0^0 orientation) was aligned with the room axes while another (135^0 orientation) was not, as shown in Figure 2-1 in section 2.3 of Chapter 2, but both were the egocentric perspective. Mental representation was updated when the viewpoint was changed from the unaligned one to the aligned one (from 135^0 to 0^0 in Figure 2-1), while mental representation was not significantly updated when the viewpoint was changed in the opposite sequence (from 0^0 to 135^0). In the present study, however, two viewpoints were egocentric and exocentric perspectives, respectively; the sequence of experiencing exocentric perspective and egocentric perspective was counterbalanced. Since the way of experiencing viewpoints in the present study was different from that in Shelton and McNamara's study, the sequence of experiencing two perspectives might influence the mental representation of the 3D room environment.

Three hypotheses were tested in the present study. First, we assumed that when subjects learned

the spatial layout from both the 45^0 exocentric and egocentric perspectives, the orientation-dependent mental representation would be still built in mind. Second, it was hypothesized that the sequence of experiencing the 45^0 exocentric perspective and the egocentric perspective could not influence the mental representation. Third and lastly, it was expected that subjects in the rectangular room would encode and represent spatial layout more accurately than their counterparts in the cylindrical room.

4.1.2 Method

(1) Subjects. Subjects in the experiment included 48 students, 24 males and 24 females, from Beijing Jiaotong University. Subjects received a monetary payment for participating in the experiment.

(2) Materials. The virtual scene was constructed in EON (Eon Reality Company, 2004), as shown in Figures 4-1 and 4-2, and was shown on i-glass Head Mounted Display (HMD, i-O Display Systems, LLC). HMD provided images at a resolution of 800×600 and a 26.5^0 diagonal field of view. Four virtual environments were created: the experimental and practice rectangular virtual rooms, and the experimental and practice cylindrical rooms. The difference between the experimental and practice rooms was that the experimental room contained seven virtual objects, whereas the practice room was empty. The rectangular room measured 8m × 6m × 6m in the virtual space, and the radius of cylindrical room was 4 m and the height was 6m in the virtual space. Seven objects (lamp, teapot, chair, missile, stoneware, hammer and pillar) were selected with the restrictions that they shared no primary semantic associations or

similar functions. This guaranteed that subjects only associated each object with its location to remember the layout in the virtual room. We also designed a set of materials for conducting the JRD task, which is introduced in the following section.

(3) Design and procedure. The independent variables included two between-subjects variables, the sequence of experiencing the perspective (exocentric-first and egocentric-first, see Figure 3-2 in section 3.1.1 of Chapter 3), the environmental geometry (rectangular or cylindrical), and one within-subjects variable, the imagined facing direction. The egocentric views in two rooms, as shown in Figure 4-1, presented the spatial layout from the viewpoint of egocentric perspective at 1.7m above the floor and 4m from the center of floor; while the exocentric view, as shown in Figure 4-2, presented the spatial layout on the floor from the viewpoint of the 45^0 exocentric perspective at about 4.5m above the floor and the viewpoint projection on the floor was 2.8m from the center of floor.
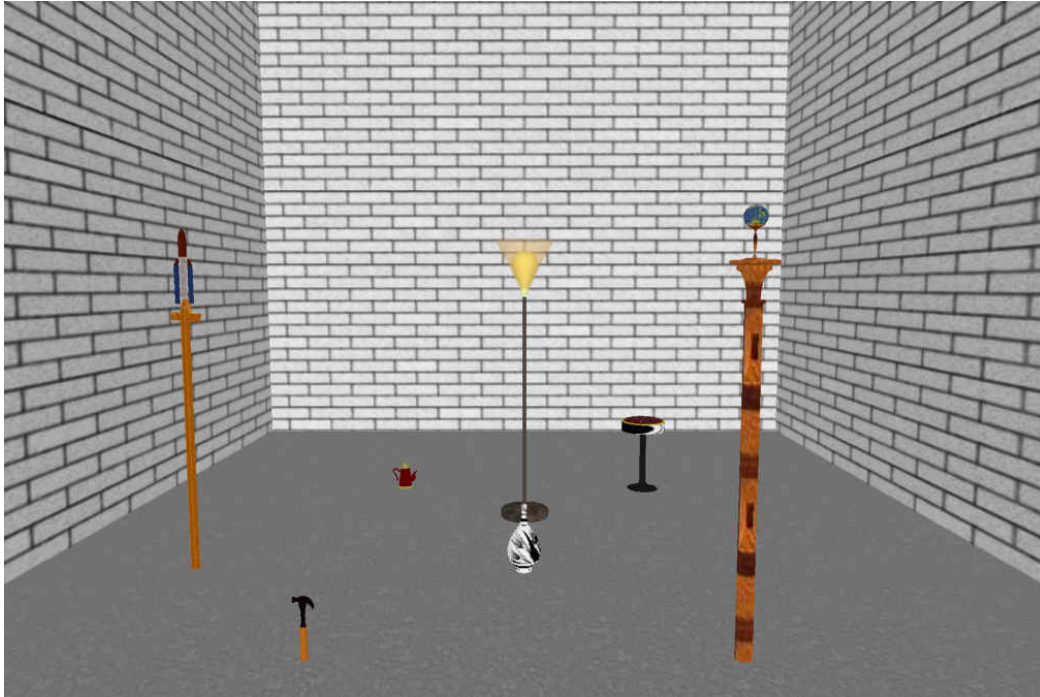
(a) the egocentric view of the rectangular room
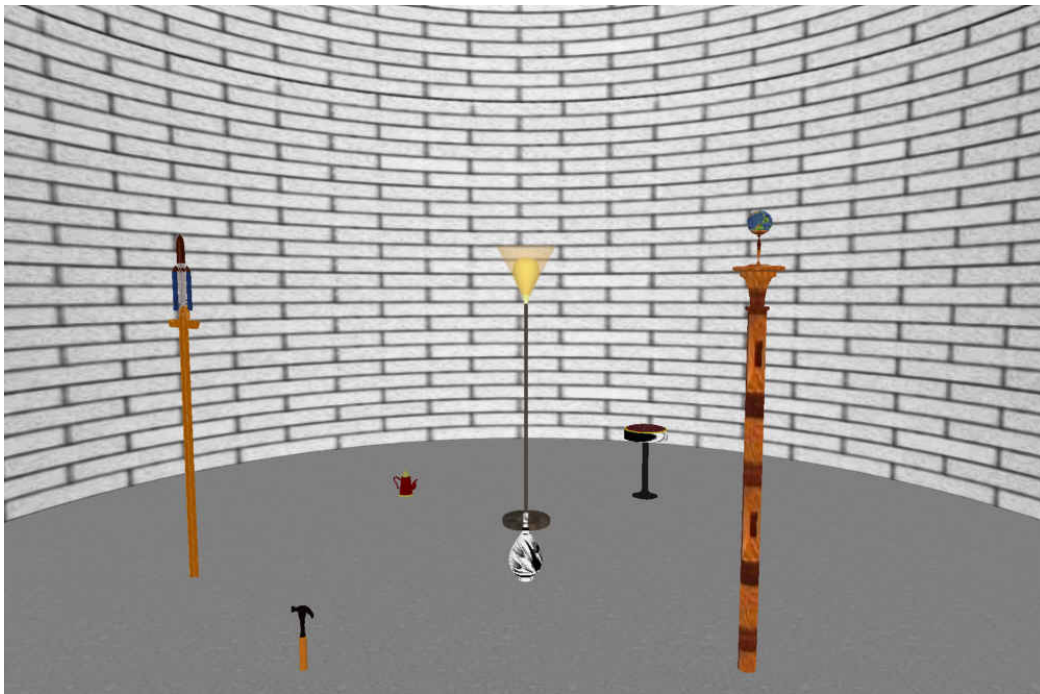
(b) the egocentric view of the cylindrical room

Figure 4-1 The egocentric views in two rooms.
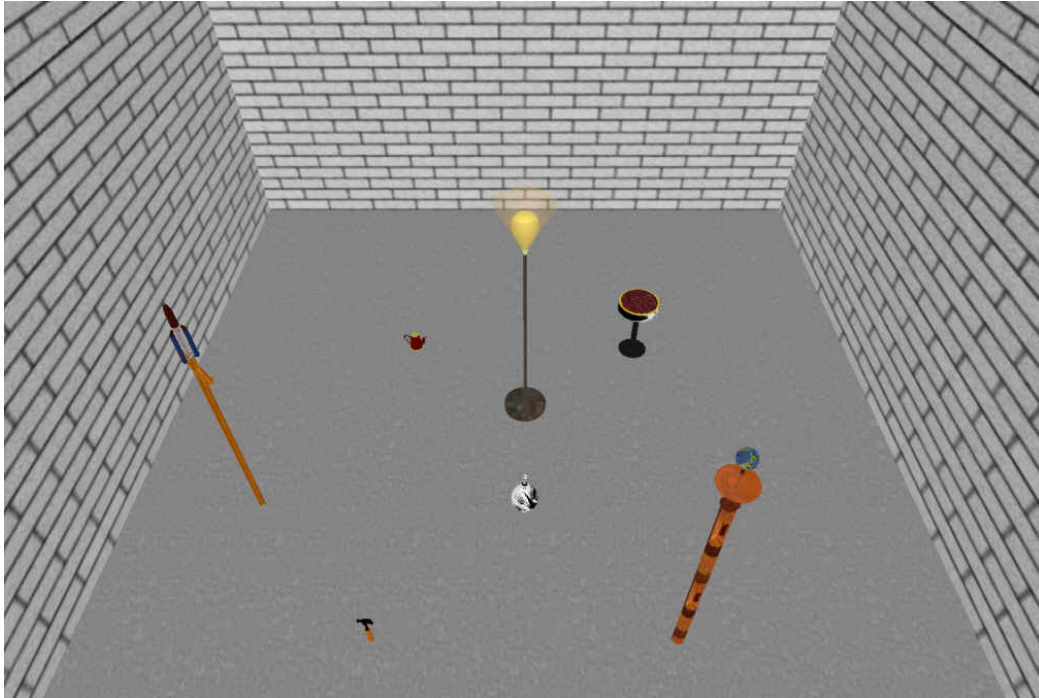
(a) the 45^0 exocentric view of the rectangular room
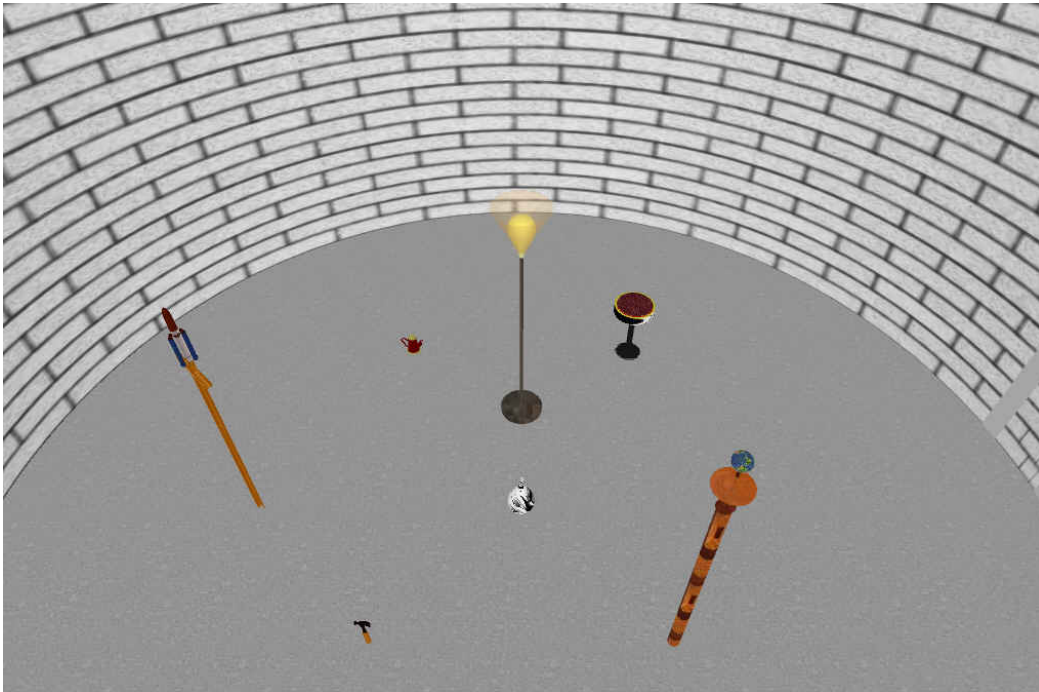
(b) the 45^0 exocentric view of the cylindrical room

Figure 4-2 The exocentric views in two rooms.

The imagined facing direction presented the horizontal relation between the standing object and the facing object required in the JRD task. The imagined facing direction could be toward to the front of the room (forward), toward the side (left/right), or toward the back of the room (backward, i.e. toward the location where subjects watched from the egocentric perspective).

Subjects were tested individually in a laboratory room. In order to screen subjects with poor memory, all subjects first took a test of memory. They were required to scan nine objects printed on a piece paper (see Appendix E) for 30 seconds and then generate these objects at the corresponding positions on a piece of blank paper of 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 assigned to four experimental conditions (2 sequences of experiencing perspectives × 2 environmental geometries) with gender balance. Subjects first observed the seven experimental objects printed as 3D objects on a paper. After they could associate each object with the unique name, they wore HMD and were instructed to practice in an empty virtual room. Subjects in the egocentric-first condition first watched the egocentric and then the exocentric views of the 3D room environment. The HMD was turned off in the process of switching these two views. Subjects in the exocentric-first condition first watched the exocentric and then the egocentric views of 3D room environment. There was no time limit in the practice till subjects felt comfortable to wear HMD and were familiar with the procedure of observation.

After the practice, subjects watched the experimental room following the same procedure as

in the practice room. They were instructed to remember the locations of objects in the room. When watching each view, they could spend two minutes remembering the locations of objects. During learning the experimenter helped them to recognize the virtual objects. After subjects finished learning, they took off HMD and performed the following spatial task.

Subjects were then asked to perform the JRD task which required employing the exocentric reference to retrieve the object-to-object relationship in memory (Easton & Sholl, 1995). When performing this task in practice, subjects stood at the mark on the ground, 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. The test environment is illustrated in Figure 4-3. Therefore, each position in the test environment could be represented by a coordinate of this system (x, y, z). In particular, the target object C in the JRD task were all in front of subjects as they imagined facing object B, so subjects would not need to point to objects behind them.

The instruction of each trial was displayed on the computer. 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. The error of horizontal angle was measured as the absolute angular difference between the pointing horizontal angle and the actual horizontal angle where the target would have been. The error of vertical angle was measured by the same method. The total time for the experiment was approximately 50 minutes.
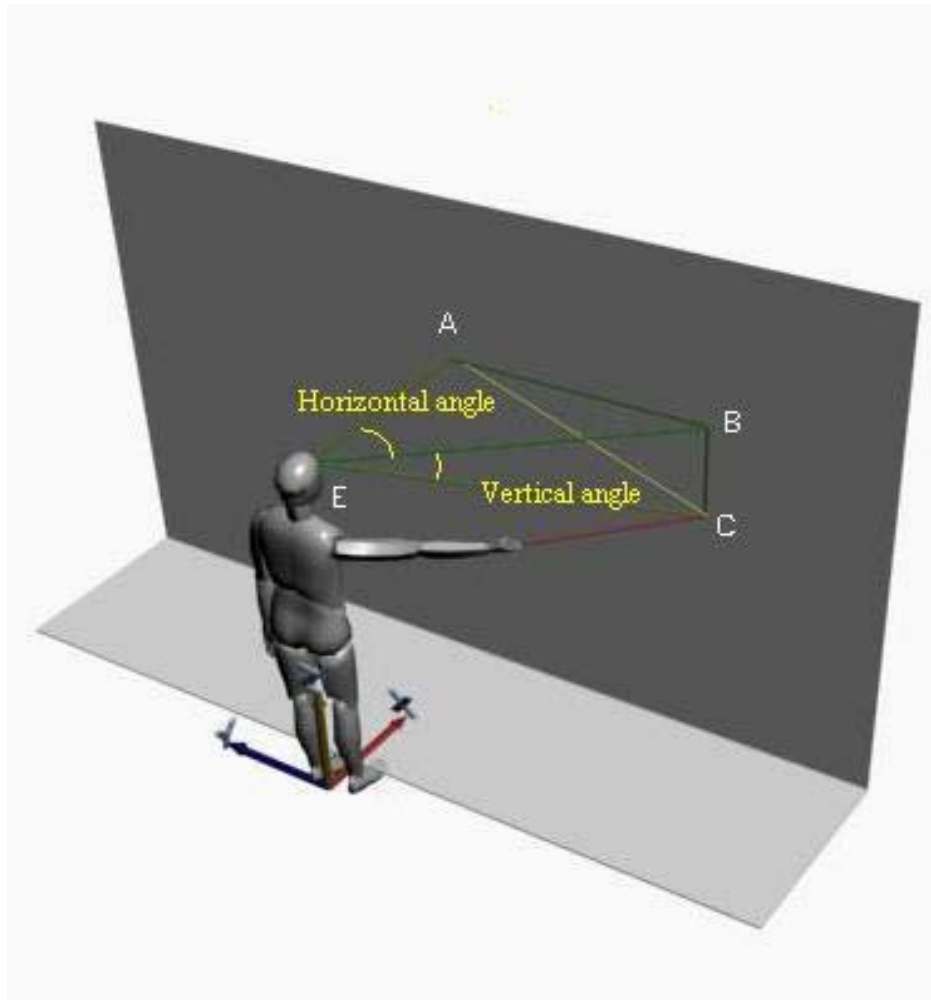
The $\angle AEB$ is the horizontal angle and the $\angle BEC$ is the vertical angle in coordinate

system labeled by X, Y and Z dimensions

Figure 4-3 Set up for performing the JRD task.

4.1.3 Results

All dependent measures were subjected to an analysis of variance (ANOVA) with terms for the sequence of experiencing two perspectives, environmental geometry and imagined facing direction. A significance level < .05 was adopted. In the following section, the results of ANOVAs on each dependent variable, including horizontal direction error, vertical direction error, and the response time are reported.

(1) The judgment accuracy of horizontal direction. The main effect of imagined facing direction, F(2, 88) = 4.07, p = .02, was significant. Multiple comparisons showed that subjects judged the relative direction between objects most accurately when imagining facing the backward direction. Neither the main effect of the environmental geometry, F(1, 44) = .02, p = .899, nor the main effect of the sequence of experiencing two perspectives, F(1, 44) = .28, p = .60, was significant.

The interaction between the imagined facing direction and the environmental geometry, $F(2, 88) = 3.57$, p = .032, see Figure 4-4, was significant. Post hoc analysis showed that the effect of imagined facing heading was only observed in the rectangular room, reflecting that the judgments of relative direction were best when subjects imagined facing the left/right direction, then facing the backward directions, and worst facing the forward direction. This result indicated that the rectangular geometry could significantly improve the representation of spatial horizontal information along the left/right direction. This improvement produced that subjects made more accurate judgments of spatial horizontal direction along the left/right direction in the rectangular room than in the cylindrical room. The interaction between the imagined facing direction and the sequence of experiencing two perspectives, $F(2, 88) = 1.71$, p = .187, and the interaction between the environmental geometry and the sequence of experiencing two perspectives, $F(1, 44) = .57$, p = .453, were not significant.
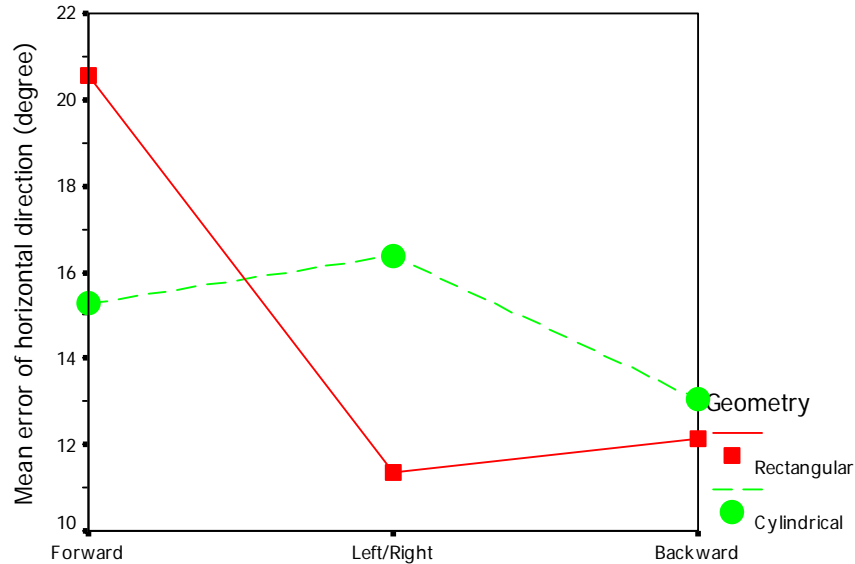
Mean horizontal angular error as a function of imagined facing direction and environmental geometry

Figure 4-4 Judgment accuracy of horizontal direction in Study 1.

The three-way interaction among imagined facing direction, sequence of experiencing perspectives and environmental geometry was significant, $F(2, 88) = 5.32$, p < .01. To understand this three-way interaction, further analyses were conducted in each room. In the rectangular room, the interaction between the imagined facing direction and the sequence of experiencing perspective was not significant, $F(2,44) = 1.64$, p = .205; while in the cylindrical room, the interaction between the imagined facing direction and the sequence of experiencing perspective was significant, $F(2,44) = 4.88$, p = .012. The results showed that the function of the sequence of experiencing the perspective was more significant in the cylindrical room than in the rectangular room.

(2) The judgment accuracy of vertical direction. The main effect of imagined facing direction, $F(2, 88) = 50.46$, p < .01, was significant. Multiple comparisons showed that the performance was best when subjects imagined facing the backward direction, and then facing the forward direction, and worst facing the left/right direction. The main effect of the environmental geometry, $F(1, 44) = 144.02$, p < .01, was significant, reflecting that the performance was significantly better in the rectangular room than in the cylindrical room. The main effect of the sequence of experiencing two perspectives, $F(1, 44) = 1.55$, p = .220, was not significant.

The interaction between the imagined facing direction and the environmental geometry, $F(2, 88) = 51.12$, p < .01, see Figure 4-5, was significant. Post hoc analysis showed that the significant effect of imagined facing direction was only observed in the cylindrical room, reflecting that subjects made less accurate judgment of relative vertical direction in the left/right direction than in the forward and backward direction. This interaction effect reflected that the cost of the cylindrical geometry was greater for the left/right direction than that of the rectangular geometry.
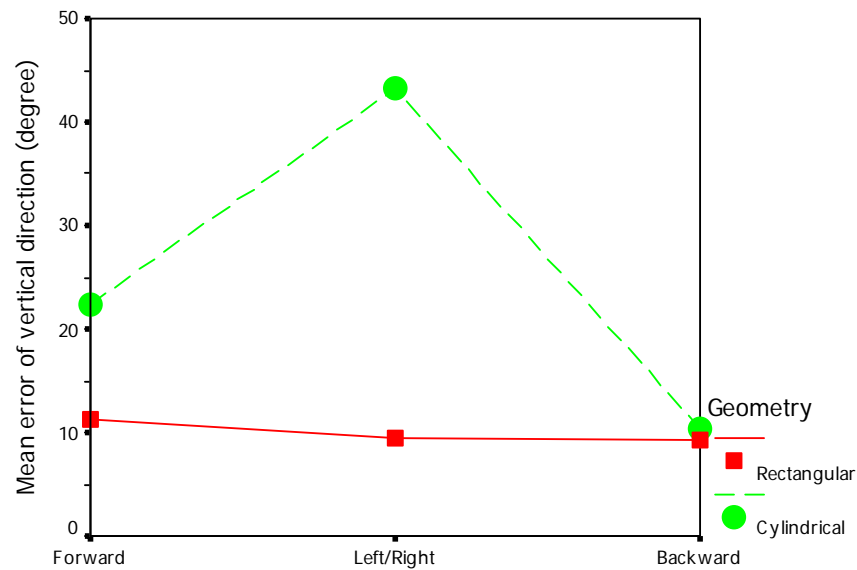
Mean vertical angular error as a function of imagined facing direction and environmental geometry

Figure 4-5 Judgment accuracy of vertical direction (a) in Study 1.

The interaction between the imagined facing direction and the sequence of experiencing two perspectives, $F(2, 88) = 2.15$, p = .123, was not significant. The interaction between the environmental geometry and the sequence of experiencing two perspectives was significant, $F(1, 44) = 4.33$, p = .043, see Figure 4-6. Post hoc analysis showed that the performance only in the cylindrical room was a bit better for subjects in the exocentric-first condition than in the egocentric-first condition. This interaction effect suggested that the benefit of experiencing the egocentric perspective later in sequence (the exocentric-first sequence) was present only in the cylindrical room where less ecologically valid features existed.
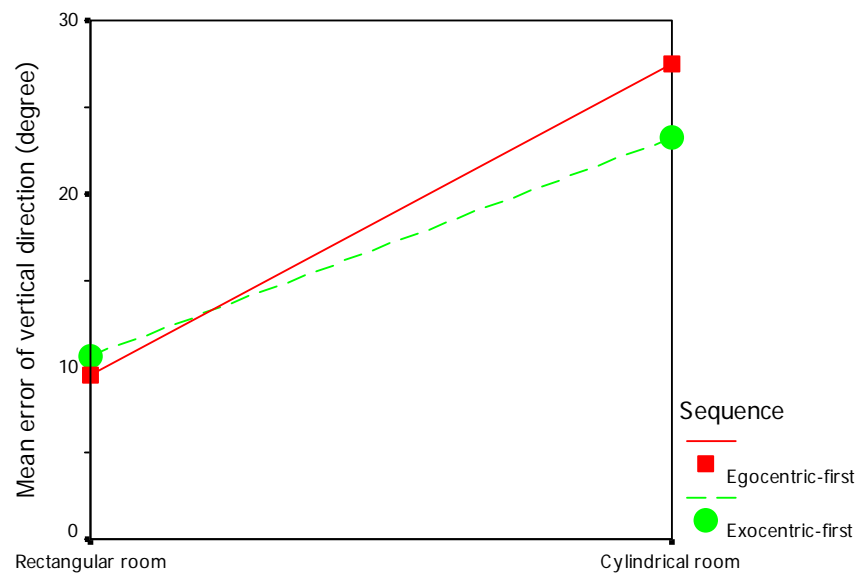
Mean vertical angular error as a function of sequence of experiencing perspectives and

environmental geometry

Figure 4-6 Judgment accuracy of vertical direction (b) in Study 1.

The three-way interaction among imagined facing direction, sequence of experiencing perspectives and environmental geometry was not significant, F(2, 88) = 2.18, p = .119.

(3) Response time. The main effect of imagined facing direction was significant, $F(2, 88) = 10.63$, p < .01. Multiple comparisons showed that subjects judged the relative direction between objects fastest when imagining facing the forward direction (the mean response time RT = 10.74 seconds), and then facing the backward direction (RT =14.66 seconds), and needed longest time when imagining facing the left/right direction (RT = 16.14 seconds). The main effect of environmental geometry, $F(1, 44) = 1.48$, p =.231, and the main effect of the sequence of experiencing two perspectives, $F(1, 44) = 2.50$, p = .121, were not significant.

The interaction between the imagined facing direction and the environmental geometry, $F(2, 88) = 1.37$, p =.260, and the interaction between the imagined facing direction and the sequence of experiencing two perspectives, $F(2, 88) = 1.71$, p = .187, were not significant. The interaction between the environmental geometry and the sequence of experiencing two perspectives was not significant, $F(1, 44) = 2.57$, p = .116.

The three-way interaction among imagined facing direction, sequence of experiencing perspectives and environmental geometry was not significant, F(2, 88) = 3.08, p = .051.

4.1.4 Discussion

The results of Study 1 showed that the orientation-dependent representation of the 3D room environment was observed, which supported our first hypothesis. First, subjects could retrieve the spatial horizontal relations between objects more accurately when imagined facing backward direction (e.g. see Figure 4-4). Second, subjects retrieved the spatial relations most quickly when imagining facing the forward direction and most slowly when imagining facing the left/right direction. In general, the orientation which was aligned with the dimension of facing direction during spatial learning was the preferred one in mental representation (Easton & Sholl, 1995; Shelton & McNamara, 2001).

The results showed that the sequence of experiencing two perspectives could not significantly affect the mental representation of the 3D room environment, which supported our second hypothesis. The interaction between the sequence of experiencing two perspectives and the environmental geometry, however, was observed to influence the representation of spatial vertical information in the 3D room environment (see Figure 4-5). This interaction indicated that when there were less ecologically valid features in the environment, experiencing the egocentric perspective later (in the exocentric-first condition) during the spatial learning would facilitate the understanding of spatial vertical information. The interaction result suggested the importance of learning from the egocentric perspective on preserving the details of spatial layout in memory(Luo & Duh, 2006b; Schafer & Bowman, 2004).

The environmental geometry was observed to influence the mental representations of spatial

horizontal and vertical information in the 3D room envrionment. For example, the rectangular geometry was observed to improve the judgments of spatial horizontal direction when subjects imagined facing the left/right direction, although the judgments were less accurate when subject imainged facing the forward direction in the rectangular room (see Figure 4-4). In comparison with the mental representation of spatial horizontal information, the benefit of rectangular geometry were more in the mental representation of spatial vertical information, especially when subjects imagined facing the left/right direction (see Figure 4-5). Although the result did not completely support our third hypothesis, they supported previous findings that the ecologically valid features can influence mental representation of the environment (e.g. Colle & Reid, 2003).

One surprise finding was that subjects in the rectangular room judged the spatial relative horizontal direction less accurately in the forward direction than in the backward direction (see Figure 4-4). This finding was not consistent with the previous finding (e.g. McNamara, 2003; Wickens, 1999). The possible reason was that the salience of object functioned as a confounding variable to influence the representation of spatial layout, and this confounding effect was more significant in the rectangular room than in the cylindrical room. The saliencies of spatial objects in this 3D room environment were different. For example, compared with the hammer, the pillar was more salient because it was more obvious and bigger. The salient object could function as a landmark to shape the representation of spatial layout (Golledge, 1999). The rectangular geometry might facilitate learning the position of this salient object since the linear shape could easily be used to connect each salient object. Therefore, the relative worse performance in the forward direction than in the backward direction, which observed in the rectangular room, was due to the relatively more salient

objects to be pointed in the backward direction.

It should be noted that one confounding factor, the environmental fidelity, could influence the spatial learning in the virtual 3D room environment. Environmental fidelity is defined to be the degree to which the VE are distinguishable from participants' observations of a real environment (Waller, Hunt, & Knapp, 1998). All spatial objects were simulated on computer, which did not fully reserve the real appearance and spatial property of each spatial object in the room environment. Because of the less fidelity, subjects might have difficulty to differentiate objects from each other, especially when they observe the spatial layout from the exocentric perspective. Therefore, in this situation, the spatial object with the big size would be easily utilized as the landmark while the spatial object with the small size would be easily neglected in memory. Meanwhile, the less fidelity generally impaired subjects to learn spatial information from the virtual 3D room since they might not be aware of some spatial information in this environment. For example, subjects responded that they could not accurately estimate the height of the lamp in this 3D room since the bulb of the lamp was a bit strange to them and had no light. We suspected that the influence of the environmental fidelity would become weak as the number of perspective increase in this virtual 3D room since subjects can acquire spatial information from different ways, for example, for example, deciding the location of object with respect to the egocentric viewpoint. This assumption will be tested in the following study.

4.2 Spatial representation and learning from multiple perspectives

4.2.1 Purpose and hypotheses

Study 2 investigated the mental representation of spatial horizontal and vertical information in the 3D room environment when subjects learned this environment from multiple perspectives. The multiple perspectives were acquired during the continuous elevation change, specifically the vertically downward movement, from the viewpoint of the 45^0 exocentric perspective to the viewpoint of the egocentric (0^0) perspective. In this new situation, the number of views was far more than two views in Study 1. In particular, the number of exocentric views would be greatly increased in the present study.

Attentive elevation and normal elevation. The elevation process to change from the 45^0 exocentric perspective to the egocentric perspective was controlled in two ways, the attentive elevation and the normal elevation (see Figure 3-3), where subjects with the attentive elevation could acquire more exocentric views than their counterparts with the normal elevation. The relatively more exocentric views were predicted to build more accurate mental representation of the 3D room environment.

Three hypotheses were examined in this study. The first hypothesis was that orientation-free representation would be built after subjects learned the environment from multiple perspectives. Second, it was expected that subjects in the attentive-elevation condition could build more accurate mental representation than their counterparts in the normal-elevation

condition. Third, subjects would represent spatial layout equally well in the rectangular and cylindrical rooms.

4.2.2 Method

(1) Subjects. Subjects included 40 students, 20 males and 20 females, from Nanyang Technological University. Subjects received monetary payment for participating in the experiment.

(2) Materials. The materials were similar to those in Study 1.

(3) Design and procedure. The design was different from that in Study 1. One new independent variable, the elevation way, was introduced to replace the variable, the sequence of experiencing perspectives in Study 1. Two elevation ways, the attentive elevation and the normal elevation, were considered, which are presented in Figure 3-3 in section 3.1.2 of Chapter 3. Therefore, the independent variables included two between-subjects variables, the elevation way (attentive and normal elevation), the environmental geometry (rectangular and cylindrical) and one within-subjects variable, the imagined facing direction (forward, left/right, backward). The dependent variables were similar to those in Study 1.

Subjects were assigned to one of four experimental conditions (2 elevation ways × 2 environmental geometries) with gender balance. Subjects also first took a memory assessment as used in Study 1, and then learned the seven experiment objects printed on the paper.

After subjects could associate each object with the unique name, they wore the HMD and were instructed to practice in a virtual empty room. Subjects first learned the spatial layout from the exocentric perspective, and then started the process of elevation (vertically downward movement) in the room. The elevation was affected by activating the down-arrow key. Subjects in the attentive-elevation condition could activate the down-arrow key after the initial observation from the exocentric perspective. For subjects in the normal-elevation conditions, their orientations in the room were first changed to be horizontal and then they could activate the down-arrow key. All subjects were required to continue activating the down-arrow key in the process of elevation until their perspectives became egocentric. Subjects could practice until they were comfortable with wearing the HMD and watching the virtual scene.

Then, subjects started learning the spatial layout in the experimental virtual room. They first spent two minutes on learning the locations of objects from the exocentric perspective. During observation, the experimenter helped them to recognize virtual objects. After learning from the exocentric perspective, they started elevating in the experimental virtual room. The elevation way was the same as one in the virtual empty room. The HMD display was turned off as soon as the perspective became egocentric. After that, subjects took off the HMD and started performing the JRD task.

4.2.3 Results

All dependent measures were subjected to an analysis of variance (ANOVA) with terms for elevation way, environmental geometry and imagined facing direction. An alpha level $p < .05$ was adopted. In the following section, ANOVAs on each dependent variable, including horizontal direction error, vertical direction error, and the response time are reported.

(1) The judgment accuracy of horizontal direction. The main effect of imagined facing direction was significant, $F(2, 72) = 8.41$, $p < .010$. Multiple comparisons showed that subjects judged the direction more accurately when imagining facing the forward or backward direction than when imagining facing the left/right direction. The main effect of environmental geometry on the judgment of horizontal direction was significant, $F(1, 36) = 7.48$, $p = .010$, reflecting that subjects in the cylindrical room judged the direction more accurately than their counterparts in the rectangular room. The main effect of elevation way was not significant, $F(1, 36) = 1.50$, $p = .229$.

The interaction between the imagined facing direction and the environmental geometry was significant, $F(2, 72) = 8.80$, p < .01, see Figure 4-7. Post hoc analysis showed that only when imagining facing the backward direction could subjects judge the direction more accurately in the cylindrical room than in the rectangular room.
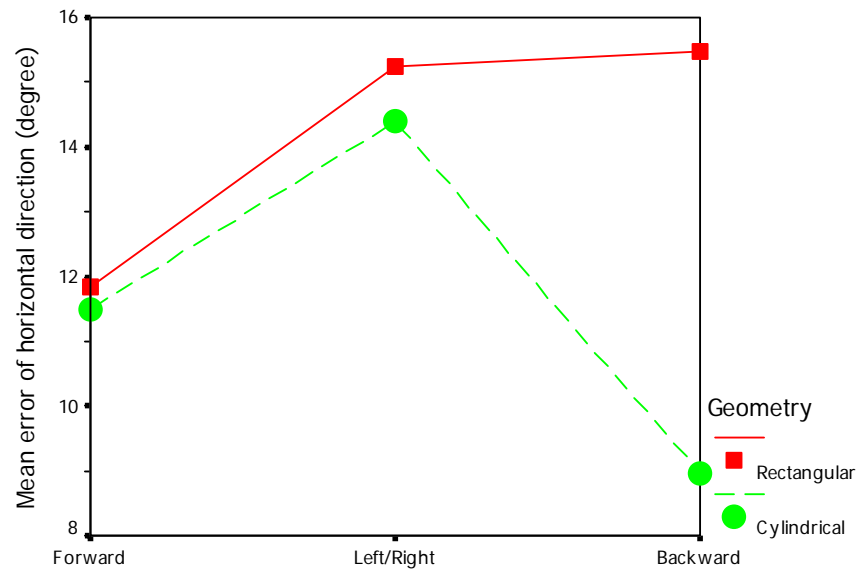
Mean horizontal direction error as a function of imagined facing direction and environmental geometry

Figure 4-7 Judgment accuracy of horizontal direction (a) in Study 2.

The interaction between the imagined facing direction and the elevation way was also significant, $F(2, 72) = 3.14$, p = .049, see Figure 4-8. Post hoc analysis showed that the effect of imagined facing direction was only observed in the attentive-elevation condition; when imagining facing the left/right direction, subjects judged the direction more accurately in the normal-elevation condition than in the attentive-elevation condition. This interaction effect indicated that the function of imagined facing direction on the mental representation of spatial horizontal information was enhanced in the attentive-elevation condition. The interaction between the environmental geometry and the elevation way was not significant, $F(1, 36) = .04$, p = .835.

Mean horizontal direction error as a function of imagined facing direction and elevation way

Figure 4-8 Judgment accuracy of horizontal direction (b) in Study 2.

However, the three-way interaction among imagined facing direction, environmental geometry and elevation way was significant, $F(2, 72) = 4.89$, p = .01. To analyze this three-way interaction, further analyses were conducted in each room. In the rectangular room,

the interaction between the imagined facing direction and the elevation way was significant, $F(2, 36) = 5.10$, p = .01; while in the cylindrical room, the interaction between the imagined facing direction and the elevation way was not significant, $F(2, 36) = 1.10$, p = .345. The results showed that the function of the attentive elevation on supporting the acquisition of spatial horizontal information was more significant in the rectangular room than in the cylindrical room.

(2) The judgment accuracy of vertical direction. The main effect of imagined facing direction was significant, $F(2, 72) = 77.70$, p < .010. Multiple comparisons showed that subjects judged the direction more accurately when imagining facing the forward or backward direction than when imagined facing the left/right direction. The main effect of environmental geometry on the judgment of vertical direction was not significant, $F(1, 36) = .61$, p = .441. The main effect of elevation way was significant, $F(1, 36) = 6.85$, p = .013, reflecting that subjects could judged the direction more accurately in the attentive-elevation condition than in the normal-elevation condition.

The interaction between the imagined facing direction and the environmental geometry was not significant, $F(2, 72) = 1.50$, p = .231.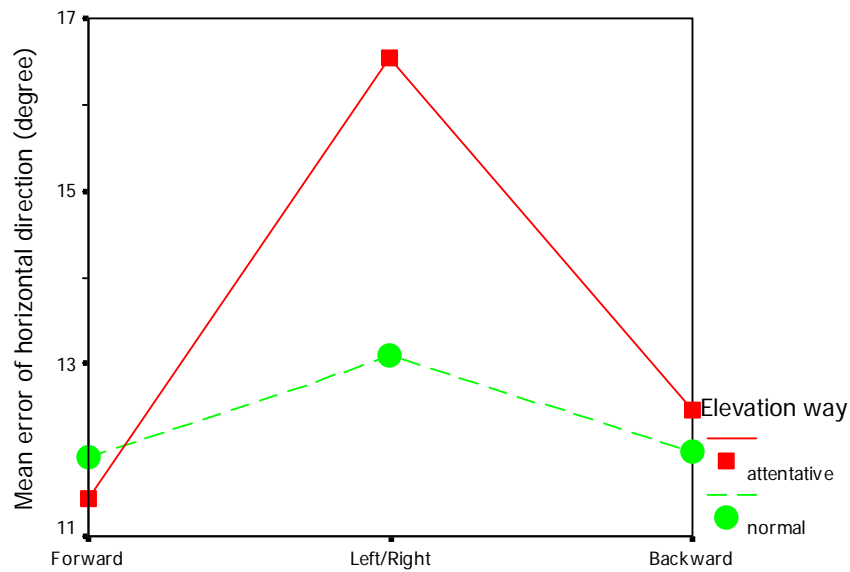 The interaction between the imagined facing direction and the elevation way was significant, $F(2, 72) = 3.93$, p = .024, see Figure 4-9. Post hoc showed that only when imagining facing the forward and left/right directions, subjects judged the direction more accurately in the attentive-elevation condition than in the normal-elevation condition. This interaction effect further supported that the attentive elevation facilitated the acquisition of spatial vertical information in the environment. The interaction between the environmental geometry and the elevation way was not significant, $F(1, 36) = 3.14$, p = .085.

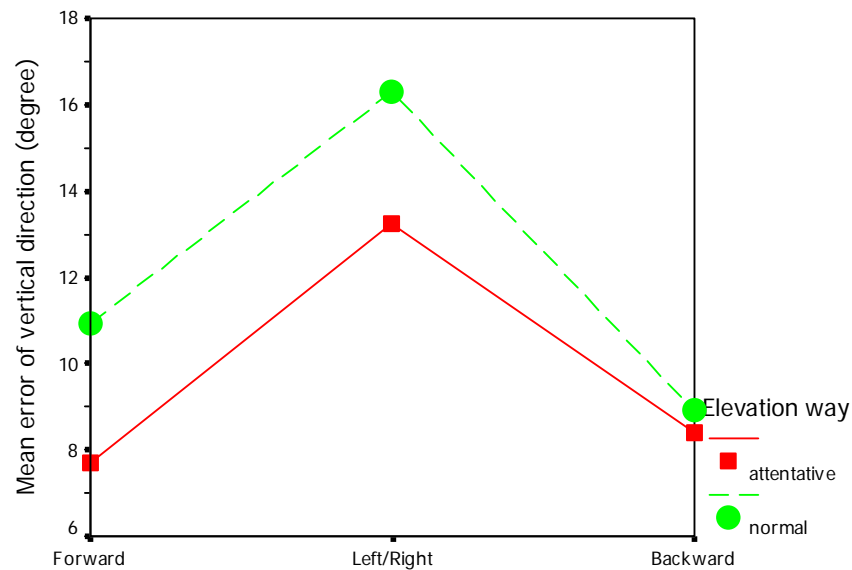Mean vertical direction errors as a function of imagined facing direction and elevation way

Figure 4-9 Judgment accuracy of vertical direction in Study 2.

The three-way interaction among the imagined facing direction, environmental geometry and elevation way was also significant, F(2, 72) = 6.38, p < .01. To analyze this three-way interaction, further analyses were conducted in each room. In the rectangular room, the

two-way interaction between the imagined facing direction and the elevation way was not significant, $F(2, 36) = 1.95$, p = .157; while in the cylindrical room, the two-way interaction between the imagined facing direction and the elevation way was significant, $F(2, 36) = 7.21$, p < .01. The results reflected that the function of the attentive elevation on supporting the acquisition of spatial vertical information was more significant in the cylindrical room than in the rectangular room.

(3) Response time. The main effect of imagined facing direction was significant, $F(2, 72) = 10.17$, p < .01. Multiple comparisons showed that subjects responded fastest when imagining facing the forward direction (response time, RT = 11.13 second), then facing the left/right direction (RT = 12.33 second), and slowest facing the backward direction (RT = 13.46 second). The main effect of environmental geometry on the response time was significant, $F(1, 36) = 7.98$, p < .01, reflecting that subjects could respond faster in the rectangular room than in the cylindrical room. The main effect of elevation way was not significant, $F(1, 36) = 2.26$, p = .142.

The interaction between the imagined facing direction and the environmental geometry was significant, $F(2, 72) = 6.96$, p < .01, see Figure 4-10. Post hoc showed that when subjects facing the left/right and backward directions, subjects responded faster in the rectangular room than in the cylindrical room; the significant effect of imagined facing direction was only observed in the rectangular room, reflecting that subjects responded slowest to judge the direction when imagined facing the backward direction. This interaction effect suggested that the rectangular geometry supported the acquisition of spatial knowledge in the environment, especially in the left/right and backward directions.
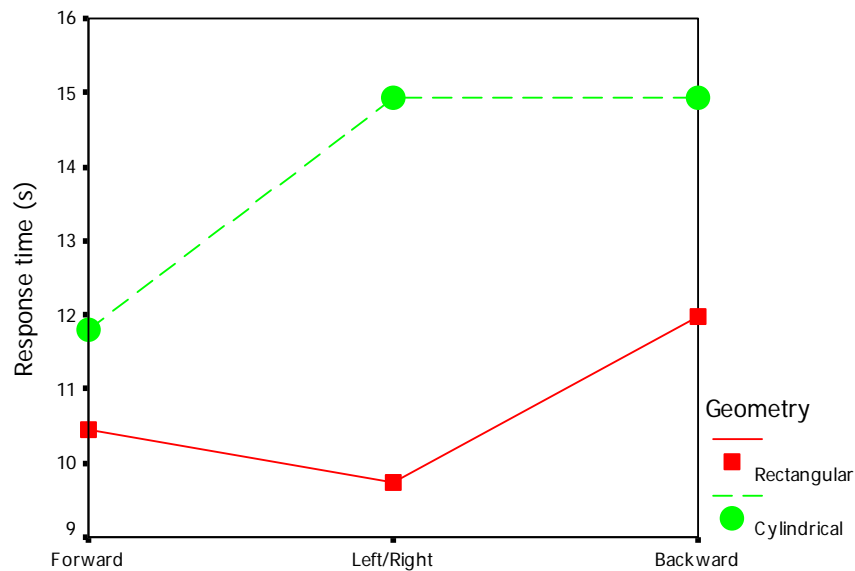
Response time as a function of imagined facing direction and environmental geometry

Figure 4-10 Response time in JRD task (a) in Study 2.

The interaction between the imagined facing direction and the elevation way was not significant, $F(2, 72) = .91$, p = .407. The interaction between the environmental geometry and the elevation way was significant, $F(1, 36) = 4.24$, p = .047, see Figure 4-11. Post hoc showed that subjects in the attentive-elevation condition responded faster in the rectangular room than in the cylindrical room; while the time difference was not significant in the normal-elevation condition. This interaction effect suggested that the benefit of attentive elevation would enhance performance in the rectangular room.
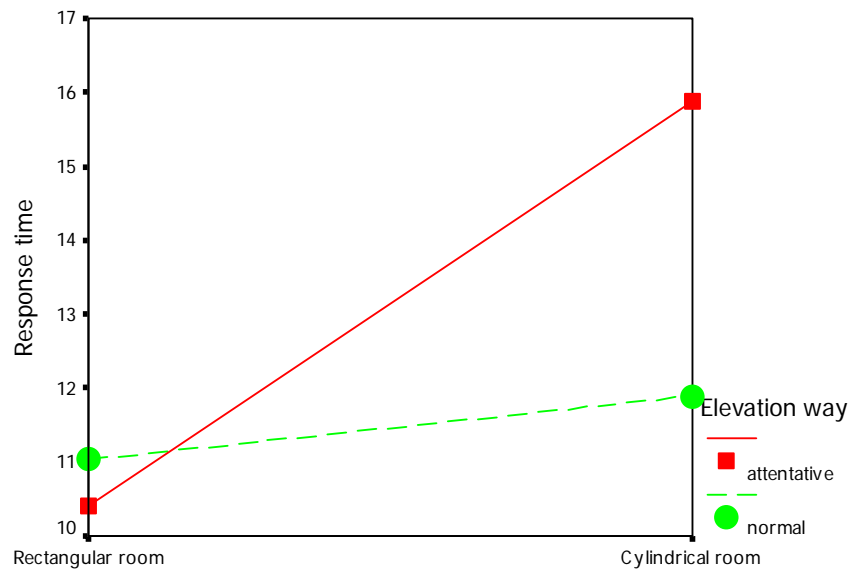
Response time as a function of environmental geometry and elevation way

Figure 4-11 Response time in JRD task (b) in Study 2.

The three-way interaction among the imagined facing direction, environmental geometry and elevation way was also significant, $F(2, 72) = 4.22$, p = .019. To analyze this three-way interaction, further analyses were conducted in each room. In the rectangular room, the interaction between the imagined facing direction and the environmental geometry was significant, $F(2, 36) = 5.21$, p = .01; while in the cylindrical room, the interaction between the

imagined facing direction and the environmental geometry was not significant, $F(2, 36) =$ 1.10, p = .345. The results reflected that the cost of the normal elevation was more significant in the rectangular room, where the perspective was aligned with the axes of rectangular room during the elevation, than in the cylindrical room.

4.2.4 Discussion

The results of Study 2 showed that the orientation-dependent representation of the 3D room environment was observed. First, subjects could retrieve the spatial relative directions between objects, including both horizontal and vertical directions, more accurately when imagining facing forward/backward direction than facing left/right direction (see Figure 4-8 and 4-9). Second, subjects retrieved the spatial relative directions most quickly when imagining facing the forward direction than facing other directions (see Figure 4-10). The data did not support our first hypothesis of Study 2. Subjects could not build the orientation-free mental representation after they learned the spatial layout from multiple perspectives along the vertical dimension of the 3D room environment.

Comparing the performance across the two elevation ways, the results showed that the judgment of spatial vertical direction between objects was more accurate in the attentive-elevation condition than in the normal-elevation condition (e.g. see Figure 4-9). The data partly supported our second hypothesis, indicating that the more views to target objects developed the better understanding of the configuration of spatial layout (e.g. Hughes & Lewis, 2005). It should be noted that the elevation way only significantly influenced the mental representation of spatial vertical information in the 3D room environment, but did not

play a significant role in facilitating the mental representation of spatial horizontal information in the 3D room environment. Furthermore, the results also showed that the preference of the attentive elevation was more significant when the environmental geometry was cylindrical, rather than rectangular.

Comparing the performance across the two environmental geometries, the results showed that (1) the judgment of spatial horizontal direction between objects was more accurate in the cylindrical room than in the rectangular room, especially when the elevation way was the normal elevation (Figure 4-7); (2) the time to judge the direction was faster in the rectangular room than in the cylindrical room, especially when the elevation way was the attentive elevation (Figure 4-10). In general, the data indicated that the environmental geometry still played a significant role in building mental representation, particularly in building the mental representation of spatial horizontal information in the 3D room environment. The data did not support our third hypothesis of the present study. Future research needs to investigate the interaction between the environmental geometry (the exocentric reference) and the perspective (the egocentric reference) on building the mental representation of the environment, especially when people can experience multiple exocentric perspectives which are not aligned with salient axes (e.g. gravity, orthogonal axes of building) of environment.

4.3 General Discussion

The results indicated that the orientation-dependent mental representation of the 3D room environment was built in mind after subjects learned the spatial layout either from two perspectives in Study 1 (e.g. see Figure 4-4) or from multiple perspectives in Study 2 (e.g. see Figure 4-8 and 4-9). Specifically, the preferred orientation in mental representation was aligned with the dimension of facing direction during spatial learning. These findings were consistent with the previous research (e.g. Easton & Sholl, 1995; Mou & McNamara, 2002; Shelton & McNamara, 2001). It should be noted that the design of this research was different from the previous research. Subjects learned spatial layout from different perspectives (including both egocentric and exocentric perspectives) in this research while subjects in the previous research learned spatial layout only from the egocentric perspective (the same egocentric perspective with different orientations). Therefore, this research demonstrated that the orientation-dependent mental representation was built across perspectives.

The effect of environmental geometry on the mental representation was observed in the present research. The existence of ecologically valid features of the rectangular room facilitated the understanding of spatial vertical information in Study 1(e.g. see Figure 4-5), which was consistent with the previous research (Colle & Reid, 2003; Hendrix & Barfield, 1997). Less ecologically valid features of the cylindrical room, however, facilitated the understanding of spatial horizontal information in Study 2 (see Figure 4-7), where subjects learned the spatial layout from multiple perspectives. Future study should pay attention to the effect of environmental geometry on spatial learning when elevation is an important part of navigation in the environment.

Mental representation of the 3D room environment was also influenced by the number of perspectives during spatial learning. For instance, subjects in the attentive-elevation condition acquired more views to target objects than their counterparts in the normal-elevation condition in Study 2. The results found that the former group represented spatial vertical information more accurately than the latter group (see Figure 4-9). Comparing the performance across two studies, we found that the effect of perspective became more significant as the number of perspectives increased. Also, subjects could acquire more accurate mental representation of the environment as the number of perspective increased from Studies 1 to Study 2. One significant improvement was the judgment of spatial vertical direction. For example, the mean vertical direction error in Study 1 (Mean $= 43.22^0$, see Figure 4-5) was decreased in Study 2 (Mean $= 16.31^0$, see Figure 4-9) when subjects imagined facing the left/right direction. In fact, comparing the data drawn in figures in these two studies, the accuracies of both horizontal and vertical direction judgments were generally improved when subjects observed the spatial layout from more perspectives. These findings demonstrated the function of exocentric views on the acquisition of survey knowledge in the environment (Gauvain & Rogoff, 1986; Rieser, Doxsey, McCarrell, & Brooks, 1982; Witmer, Sadowski & Finkelstein, 2002).

Another improvement was that the more views to spatial layout overcome the confounding factor introduced by the different saliencies of objects in spatial layout and the less fidelity of the simulated environment. As discussed in section 4.1.4 (page 75), this spatial objects with the function or perception salience produced the least accurate judgment of the spatial horizontal direction when facing the forward direction in the rectangular room (see Figure

4-4). On the contrary, when subjects learned the spatial layout from more views in Study 2, the judgment of spatial horizontal direction was more accurate in the forward direction than in other directions (see Figure 4-7). This improvement indicated that the more exocentric views facilitated the acquisition of survey knowledge in the 3D room environment, since the influence of salient objects (landmarks) on shaping the representation was not significant in survey knowledge (Siegel & White, 1975). Moreover, the improvement of the accuracy of the mental representation indicated that he less environmental fidelity could not significantly influence spatial representation and learning when more views of the 3D room environment were provided in Study 2.

It should be noted that the judgment of spatial direction in the backward direction was not least accurate in the present study. For example, the judgment of spatial horizontal direction in the cylindrical room in Study 2 (see Figure 4-7) was even the most accurate one in all three direction judgments. The result indicated that the categorical strategy can mediate mental rotation costs to retrieve spatial information (see Wickens, Vincow, & Yeh, 2005). Subjects might apply a direct strategy, for example, "back is front", when the imagined facing direction and the forward view were in direction opposition through an 180^0 rotation. Because of this strategy, mental rotation costs are not always as great as would be predicted by the linear function when there is 180^0 misalignment (Aretz, 1991). The less cost of mental rotation caused the relatively better judgments of spatial direction when subjects imagined facing backward direction.

4.3.1 Mental representations of spatial horizontal and vertical information

Across two studies, the results indicated that mental representations of spatial horizontal and vertical information in the 3D room environment were different in the mind. The results were consistent with findings in the previous research (e.g. Gäling, Böök, Lindberg, & Arce, 1990). Our explanation of these two different representations was that spatial horizontal and vertical information are encoded and represented with respect to different reference systems in human memory. Furthermore, as the number of perspectives increased, the reference system with respect to which spatial information was represented in memory was updated.

4.3.1.1 Different representations acquired from two perspectives

The mental representations of spatial horizontal and vertical directions were different in Study 1 when subjects learned spatial layout in the 3D room environment from two perspectives. First, both the sequence of experiencing perspectives and the environmental geometry did not significantly influence the representation of the spatial horizontal information. One possible explanation was that the spatial horizontal information was represented with respect to the local reference defined by the layout structure itself, similar to the intrinsic axis suggested in McNamara's spatial memory model (e.g. McNamara, 2003, see section 2.1.4 of Chapter 2). Neither the room geometry (the global reference) nor the egocentric viewpoint or perspective (the egocentric reference) was selected as the reference to encode and represent the spatial horizontal information.

Second, the environmental geometry significantly influenced the mental representation of

spatial vertical information (see Figure 4-5). The data indicated that the mental representation of the spatial vertical information was determined by the global reference (the room wall around spatial layout). The ecologically valid features of the rectangular room, such as the linear shape, facilitated to building the mental representation of spatial vertical information. Hendrix and Barfield (1997) suggested that the reconstructed reference in the mind for organizing spatial vertical relations was determined by the ecological cues in the environment.

4.3.1.2 Different representations acquired from multiple perspectives

As the number of perspective increased in Study 2, the mental representations of spatial horizontal and vertical directions were still different. The reference system, however, was different from the one observed in Study 1. First, the environmental geometry played the main role in building the mental representation of spatial horizontal information. Specifically, subjects in the cylindrical room better represented the spatial horizontal information than their counterparts in the rectangular room (e.g. see Figure 4-7). The elevation way, both attentive elevation and normal elevation, did not significantly influence the mental representation of spatial horizontal information, but did interact with the environmental geometry and the facing orientation to influence this mental representation.

Second, the elevation way, which generated multiple views of spatial layout, significantly influenced the mental representation of spatial vertical information in the environment. Specifically, the more views of spatial layout (in attentive-elevation condition) subjects watched, the more accurate the mental representation of spatial vertical information was (e.g. see Figure 4-9). This finding was consistent with the previous research (e.g. Hughes & Lewis,

2005), suggesting that the attentive elevation would be one effective way of learning spatial vertical information. The environment geometry, however, did not significantly influence the representation of spatial vertical information, but interacted with the elevation way and the facing orientation to influence this mental representation.

In summary, mental representations of spatial horizontal and vertical information in the 3D room environment were encoded and represented with respect to different frames of reference. As McNamara's spatial memory model (McNamara, 2003) pointed out, the selection of reference to define the mental representation of the environment is influenced by many factors, for example the learning experience (such as two and multiple perspectives in the present two studies) and the environmental geometry (such as rectangular and cylindrical shapes). There is a competition among these factors to determine the preferred reference system with respect to which the spatial information is represented in (Carlson, 1999).

In closing, certain factors of the present two studies may confound the findings. First, the small field of view (FOV) of the HMD might impair the observation of the room environment and the acquisition of spatial knowledge. Subjects lost some peripheral vision in extracting the spatial information from the environment. Second, the 3D view displayed on the HMD might have some perceptual costs. For instance, the 3D display typically leaves some ambiguity regarding the precise position of an object along the line of sight, and loses resolution in depicting the motion or position along the viewing axis (Wickens, 2002). Finally, subjects simulated the downward movement by activating the down-arrow key. The motion of vertical movement was provided by the optical flow in the visual scene. This might lead to the bias in perceiving the height when subjects changed elevation in the environment.

Chapter 5 Spatial Representation and Learning in Multilevel Buildings

The main purpose of two studies (Studies 3 and 4) introduced in this chapter is to investigate the mental representation of spatial horizontal and vertical information in multilevel buildings, with focus on testing three biases in mental representation and the function of the 3D map on influencing this mental representation.

Spatial bias in the mental representation. Since a multilevel building is a constrained three-dimensional (3D) environment with the constraints of walls, ceilings and floors, and navigation in a multilevel building is limited within specific areas, such as on floors and staircases, spatial biases are observed in the mental representation of this constrained environment. Three spatial biases were the focus in the present two studies: vertical same level bias (Montello & Pick, 1993; Richardson, Montello, & Hegarty, 1999), downward bias (Wilson, Foreman, Stanton, & Duffy, 2004), and preferred orientation (Shelton & McNamara, 1997). It was expected that these three biases would be observed in these two studies.

3D map. How do we overcome these biases in mental representation of the multilevel building? The present two studies investigated the function of the 3D map on influencing this mental representation. The 3D map rendered an exocentric view of the target environment in one medium (e.g. paper or display), which was similar with the exocentric view watched from the exocentric perspective. The 3D map has been demonstrated to aid pilot's navigation in the 3D natural environment (e.g. Wickens, Vincow & Yeh, 2005) and to improve the

understanding of verticality in the constrained building space (e.g. Fontaine, 2001). Therefore, it was expected that the three spatial biases in the mental representation would be weak or even overcome when the multilevel building was augmented with the 3D map.

Environmental complexity. Environmental features can influence human's spatial perception and cognition to the environment structure, especially in the building environment (Lynch, 1960; Passini, 1984). One important feature, the environmental complexity, was considered in present research. The environmental complexity was operationalized by the environmental geometry, size, the amount of spatial objects, and the spatial structure of the building (see section 3.2 in page 51). In this research, subjects navigated one simple multilevel building in Study 3 and one complex multilevel building in Study 4. The effect of environmental geometry on mental representation of the environment has been observed in Studies 1 and 2 introduced in Chapter 4. Previous research also finds that the size of environment can influence mental representation. For instance, Sovrano and Vallorigara (2006) pointed out that spatial orientation mainly relies on the geometric information in the small environment and the landmark information in the large environment. Weisman (1981) found that subjects felt it more difficult to remember and integrate the successive views when the complexity of the layout increased. Given that the 3D map can improve the acquisition of survey knowledge, it was expected that the use of the 3D map could play a more significant role in the complex multilevel building than in the simple multilevel building.

5.1 Spatial representation and learning in a simple multilevel building

5.1.1 Purpose and hypotheses

The purpose of Study 3 was to reveal the characteristics of the mental representation of the simple multilevel building and the function of the 3D map on influencing this mental representation. Subjects navigated a grid-like vertically aligned three-level building. The multilevel building was augmented with either a 3D building map, a 3D floor map, or neither, where the 3D floor map illustrated the 3D spatial layout on each floor while the 3D building map illustrated the 3D spatial layout across all floors into one rendering. The mental representation of this building was measured by the judgment of relative direction (JRD) employed in previous two studies discussed in Chapter 4 (see section 4.2).

Three hypotheses were examined in the present study. The first two hypotheses were introduced above: (1) the three spatial biases, vertical same level bias, downward bias, and preferred orientation, would be found in the mental representation of the multilevel building; (2) the three spatial biases in the mental representation would be weak or even overcome when the multilevel building was augmented with the 3D map. The third hypothesis was that the 3D building map, compared with the 3D floor map, could facilitate the acquisition of survey knowledge better since only the former illustrated additional vertical relationships between levels (Fontaine, 2001).

5.1.2 Method

(1) Subjects. There were 40 undergraduate and graduate students, 20 males and 20 females, from Nanyang Technological University, participating in this experiment for monetary compensation. They had normal or corrected-to-normal vision.

(2) Materials. A Pentium IV HP xw4300 workstation with a 19-in. monitor was used to display VEs created by using the 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 comprised of three vertically aligned rooms that formed a three-level building (see Figure 5-1). The room on each floor 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—2×2m wide—that connected all three rooms. The elevator had one door that was open to the room and closed 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) in the experimental building, three in each room.
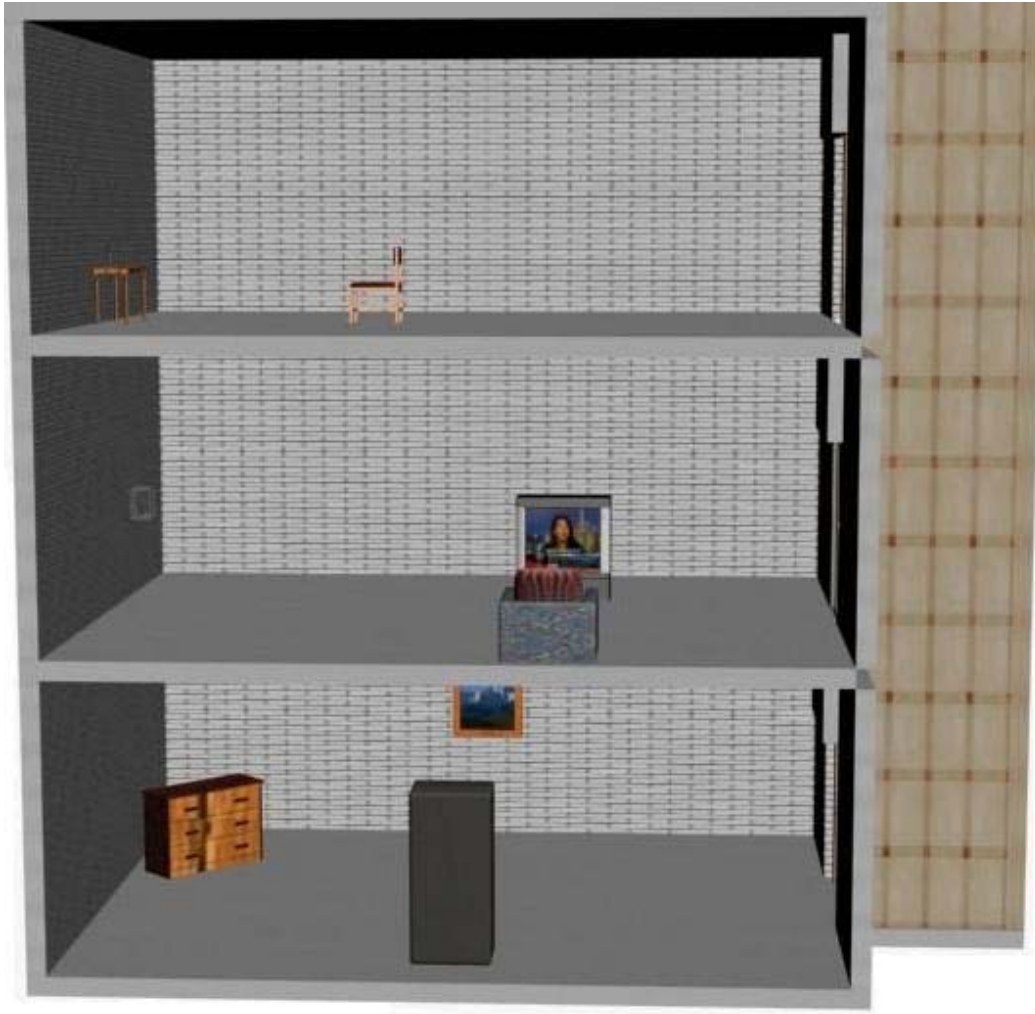
There are three objects on each level and an elevator at the right side connects all three levels.

Figure 5-1 The design of vertically aligned three-level building in Study 3.

The 3D floor map presented the layout of floor from the viewpoint 4 meters above each level, looking forward from the elevator. The 3D building map presented the layout of whole building from the viewpoint 9.8 meters above the lower level (see Figure 5-2). The geometric field of view (GFOV) of the exocentric map was set at 74^0 in the horizontal axis and 59^0 in the vertical axis. Specifically, the size of 3D map was 10.2cm×8.1cm, which was embedded in the 3D immersive view.
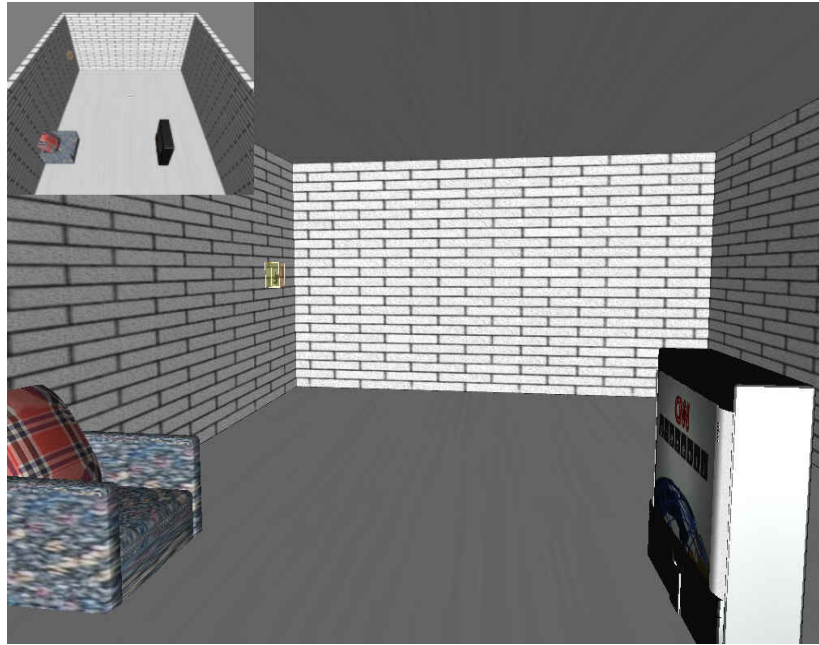
(a) The view in the 3D floor-map condition; the small map at the top left is the floor map
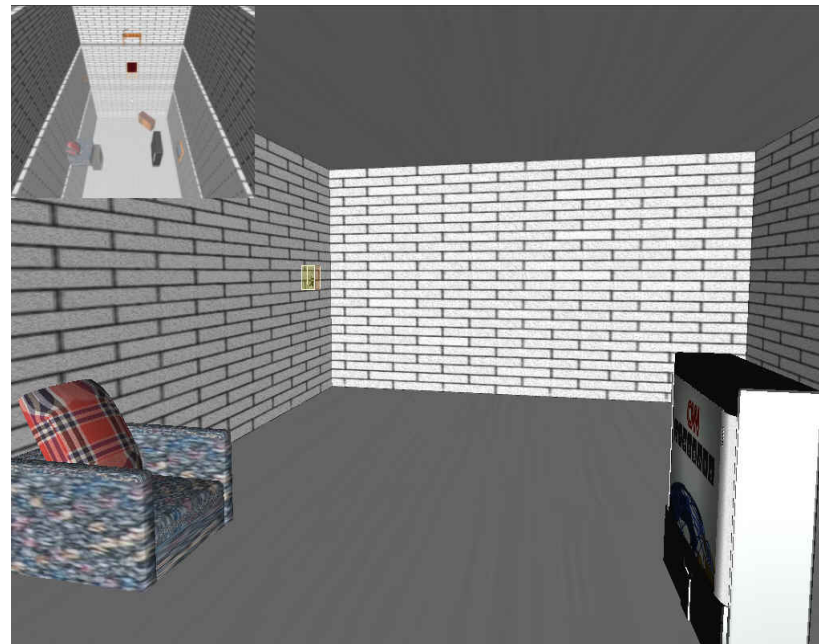
(b) The view in the 3D building-map condition: the small map at the top left is the building

map in which two transparent floors are rendered.

Figure 5-2 Immersive views in 3D floor and building maps conditions in Study 3.

(3) Design and procedure. The independent variables included one between-subjects variable which defined four kinds of navigation treatment— no map, 3D floor-map, 3D building-map and transparent conditions — and two within-subjects variables—the level difference and the imagined facing direction. The dependent variables were the angular error and the response time recorded in the JRD task performed after navigation in the environment. There were two angular errors: the error of horizontal angle and the error of vertical angle.

Specifically, the no map group was the control group, in which subjects explored the virtual building without any aid. In the 3D floor map and 3D building map conditions, the 3D map would be always displayed in the up-left corner within subject's egocentric view. The 3D floor map showed the layout of the level on which subjects were standing at that moment. When subjects arrived on a new level, the content of a 3D floor map was automatically changed to show the new level layout. Checking the 3D floor map, to some degree, was similar with learning the spatial layout from the 45^0 exocentric perspective in Study 1. Subjects assisted by the 3D floor map could acquire an exocentric view of each level. The 3D building map simultaneously rendered all spatial layouts across three levels as viewed from a downward angle above the third level – the upset level. The upper two levels were set to be transparent so that the viewer could see objects on the two levels below. The 3D building map would not change during navigation.

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

perspectives when the elevator arrives or leave one level. It was similar to the situation in the normal-elevation condition in Study 2.

The subjects were randomly assigned into each of four treatment groups and were tested individually in a quiet room. In order to screen subjects with the poor memory, all subjects first took a test of spatial memory, which was used in previous two studies.

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. Maps were not given to subjects in the two map conditions at this time 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 be near 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 navigating the building, subjects were asked to perform the JRD task. The test environment was the same as one in previous two studies introduced in Chapter 4 (see section 4.2.2). The total time for the experiment was approximately 60 minutes.

5.1.3 Results

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 < .05 was adopted for all these analyses. The relative means are shown in Table 5-1.

(1) The judgment accuracy of horizontal direction. The main effect of the navigation treatment was significant, $F(3, 36) = 3.11$, p < .05. Multiple comparisons showed that the performance was significantly worse under the no-map than under the other three conditions; the remaining three conditions did not differ significantly. As depicted in Figure 5-3, the main effect of level difference was significant, $F(4, 144) = 24.15$, p < .01. Multiple comparisons showed that 1) the best performance (lowest error) was observed when subjects pointed to objects on the same level, and 2) the performance was better when pointing up than pointing down. The interaction between the navigation treatment and the level difference was not significant.

Table 5-1 Mean accuracy (degree) and response time (second) of direction judgment in Study 3

Measure	Navigation treatment	Level difference							Imagined facing direction				
		Two down	One down	Same	One Up	Two Up	Total	Sig	Forward	Left/Right	Backward	Total	Sig
Error of horizontal angle	No map	27.72	32.37	7.93	19.69	16.84	20.91	*	7.93	23.13	24.34	18.47	*
	3D floor map	21.61	25.36	9.76	12.82	11.25	16.16	*	9.76	14.28	20.76	14.94	*
	3D building map	15.9	25.39	8.57	13.94	12.73	15.29	*	8.57	15.68	19.25	14.51	*
	Transparent	16.49	29.19	7.1	11.04	10.45	14.85	*	7.1	13.08	21.84	14	*
	Total	20.43	28.06	8.34	14.37	12.82			8.34	16.54	21.55		
	Sig	n.s.	n.s.	n.s.	n.s.	n.s.			n.s.	*	n.s.		
Error of vertical angle	No map	12.26	9.5	5.33	13.96	22.47	12.7	*	5.33	17.23	11.73	11.43	*
	3D floor map	22.74	8.55	7.25	18.8	24.46	16.36	*	7.25	22.93	11.55	13.91	*
	3D building map	12.26	7.65	5.34	11.8	23.13	12.04	*	6.1	15.78	10.55	10.81	*
	Transparent	14.97	9.79	7.14	13.8	20.37	13.21	*	7.14	17.43	11.06	11.87	*
	Total	15.56	8.87	6.26	14.59	22.61			6.45	18.34	11.22		
	Sig	*	n.s.	n.s.	n.s.	n.s.			n.s.	*	n.s.		
Response time	No map	33.9	17.65	18.73	24.4	22.8	23.5	n.s.	19.97	25.48	19.67	21.7	n.s.
	3D floor map	21.5	23.65	17.37	23.45	15.3	20.25	n.s.	17.37	18.4	24.23	20	n.s.
	3D building map	19.2	19.35	16.37	16.85	17.5	17.85	n.s.	16.37	17.5	18.87	17.58	n.s.
	Transparent	20.7	23.45	16.07	24.95	18.1	20.65	n.s.	16.07	18.75	26.23	20.35	n.s.
	Total	23.83	21.03	17.13	22.41	18.43			17.44	20.03	22.25		
	Sig	n.s.	n.s.	n.s.	n.s.	n.s.			n.s.	n.s.	n.s.		

Note—* indicates significant (<.05); n.s. indicates not significant
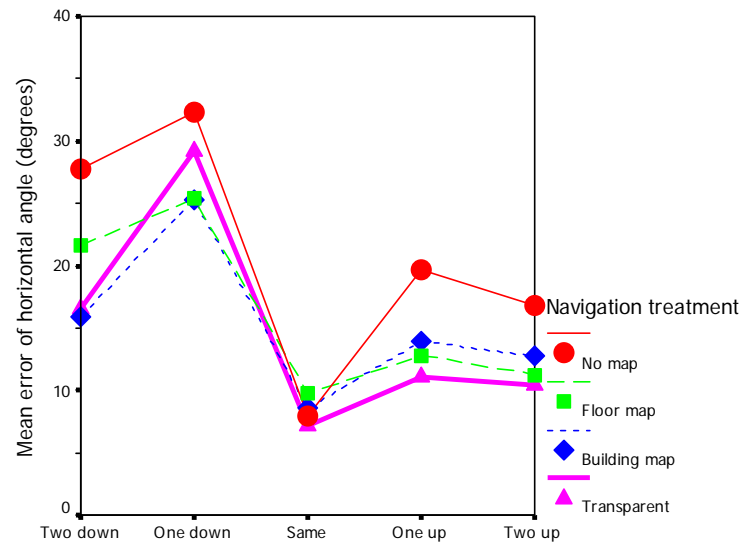
Mean horizontal direction errors as a function of the level difference and the navigation treatment

Figure 5-3 Judgment accuracy of horizontal direction (a) in Study 3.
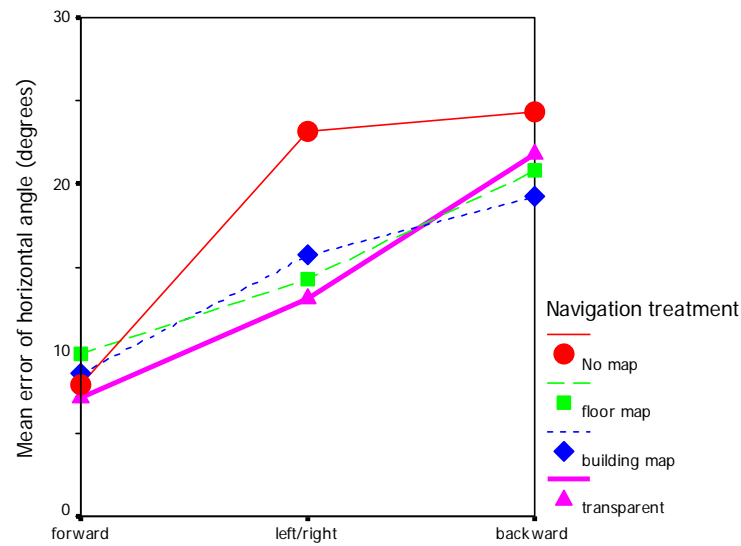
Mean horizontal direction errors as a function of the imagined facing direction and the navigation treatment

Figure 5-4 Judgment accuracy of horizontal direction (b) in Study 3.

As depicted in Figure 5-4, the main effect of the imagined facing direction was significant, $F(2,72) = 47.85$, p < .01. Multiple comparisons suggested that the performance in the forward facing direction (i.e. the orientation from which they entered the room) was the best and in the backward (i.e. the orientation from which they exited the room) was the poorest. The interaction between the navigation treatment and the imagined facing direction was not significant.

(2) The judgment accuracy of vertical direction. The main effect of navigation treatment was significant, $F(3, 36) = 4.34$, p = .01, where the performance was worse in the 3D floor map condition than in the other three conditions. As depicted in Figure 5-5, the main effect of level difference was significant, $F(4, 144) = 31.8$, p < .01, reflecting the following three trends: (1) the best vertical pointing occurred when the target object was on the same level; (2) performance was worse on pointing the target object on more distant than on closer levels; (3) performance was better when pointing down than when pointing up. The interaction between the navigation treatment and the level difference was not significant.

The main effect of the imagined facing direction was also significant, $F(2,72) = 64.12$, p < .01. As shown in Figure 5-6, again, subjects estimated the vertical direction more accurately when imagined facing forward direction than when imagined facing other directions and the pointing towards left/right was least accurate. The interaction between the navigation treatment and the imagined facing direction was not significant.

Mean vertical direction errors as a function of the level difference and the navigation treatment

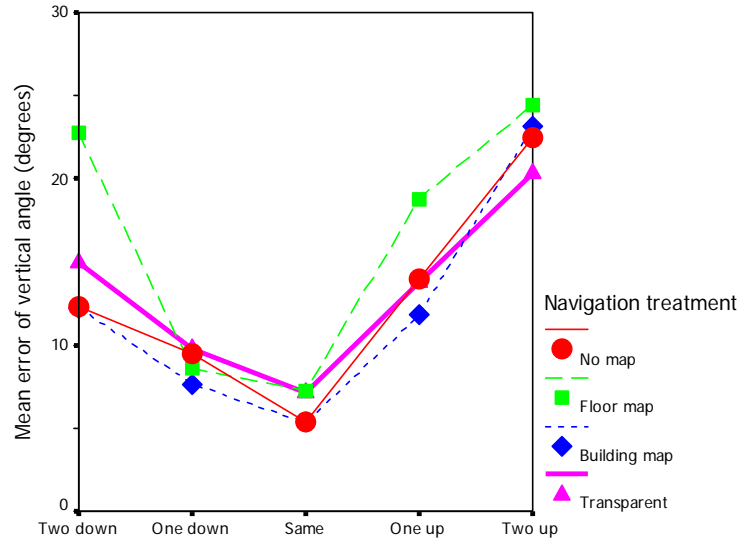Figure 5-5 Judgment accuracy of vertical direction (a) in Study 3.
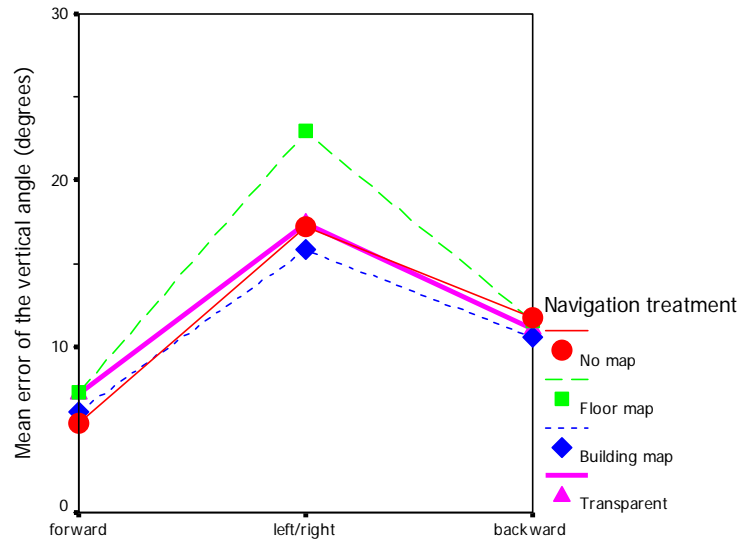
Mean vertical direction errors as a function of the imagined facing direction and the navigation treatment

Figure 5-6 Judgment accuracy of vertical direction (b) in Study 3.

(3) Response time. Navigation treatment did not show significant main effect on response time. There was a significant effect of level difference, $F(4, 144) = 4.27$, p < .01, and pointing to objects on the same level was fastest. The interaction between the navigation treatment and the level difference was significant, $F(12, 144) = 1.88$, p < .05. Post hoc analysis indicated that the judgments under the 3D building map condition were relatively unaffected by the level differences while the judgments under other three conditions were affected in various ways (see Figure 5-7).

The main effect of the imagined facing direction was significant, $F(2, 72) = 6.776$, p < .01. The interaction between the navigation treatment and the imagined facing direction was significant, $F(6, 72) = 2.98$, p < .05. Post hoc analysis showed that only in the no map treatment was the response time affected by imagined facing direction, suffering most when subjects imagined facing left or right (see Figure 5-8).
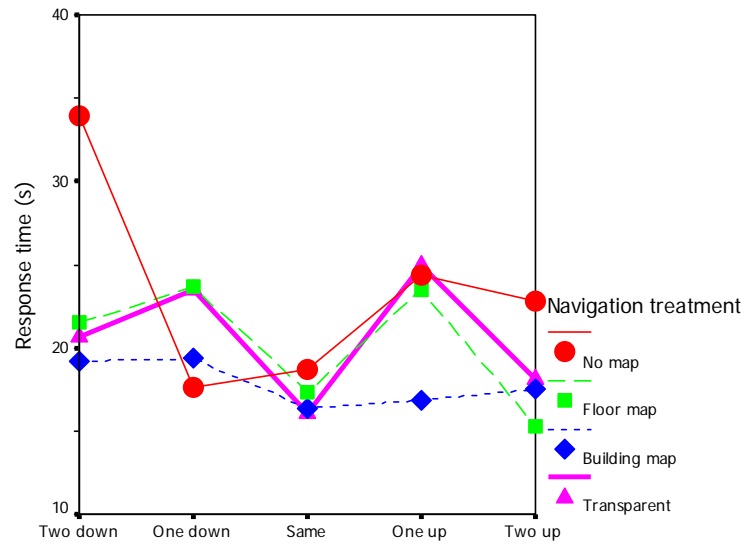
Mean response time as a function of the level difference and the navigation treatment

Figure 5-7 Response time in JRD task (a) in Study 3.
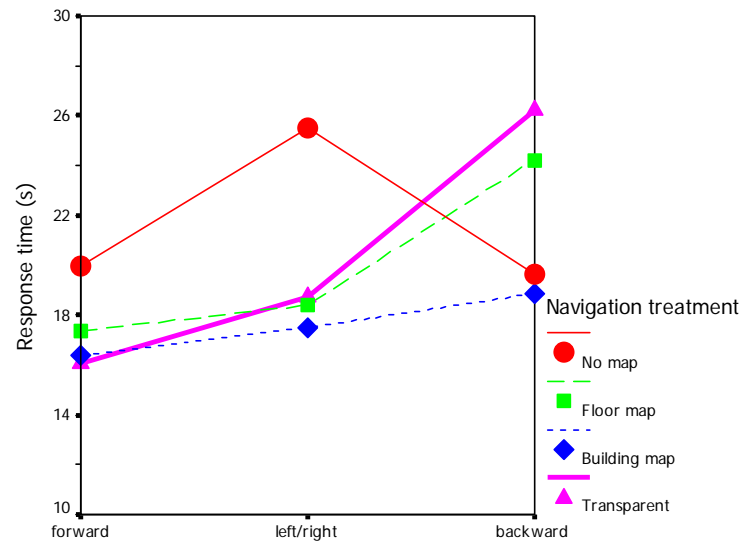
Mean response time as a function of the imagined facing direction and the navigation treatment

Figure 5-8 Response time in JRD task (b) in Study 3.

5.1.4 Discussion

The results of Study 3 showed that the three biases of spatial memory were observed, which supported our first hypothesis in the present study. First, subjects estimated both horizontal and vertical directions (see Figures 5-3 and 5-5) more accurately when the target objects (C) and the reference objects (A and B) were on the same level rather than on different levels. This result indicated that the vertical same-level bias is a strong attribute in the mental representation of multilevel building, regardless of whether or not a 3D map is used.

Second, the angular error of vertical direction (see Figure 5-5) demonstrated that subjects made the downward pointing more accurately than they made the upward pointing, which supported the previously observed downward bias in memory (Wilson, et. al, 2004a, b). Also, the 3D floor map which could not depict the vertical relations between levels significantly impaired the knowledge of spatial vertical relations in memory. As shown in Figures 5-5 and 5-6, the judgment of vertical direction following navigation with the 3D floor map was worse than those in the other three conditions, including the no map condition. In contrast, the angular error of horizontal direction (see Figure 5-3) revealed that the subjects made more accurate judgments in the upward direction than in the downward direction. The distinct effects of level difference on estimating horizontal and vertical directions of objects suggested that the mental representations of vertical direction and the horizontal direction are relatively independent (Gärling, Böök, Lindberg, & Arce, 1990).

Third, subjects estimated horizontal and vertical directions more accurately when imagining facing the forward direction than when imagining facing left/right or backward direction (as

depicted in Figure 5-4 and 5-6). This indicated that the bias of preferred orientation is also a strong attribute in the mental representation, despite the use of 3D map. This result extended the finding in the literature that the preferred orientation existed when people used the traditional 2D map for spatial learning (e.g. Sholl, 1999; Wickens, Vincow & Yeh, 2005). It should be noted that the judgments of spatial vertical direction in the left/right direction were even worse than those in the backward direction (see Figure 5-6). The data supported again that the category strategy did be applied by subjects to mediate mental rotation costs to retrieve spatial information (Aretz, 1991, also check the discussion in section 4.3).

Comparing the performance across four conditions with or without a map showed that, in general, the performance in the 3D building map condition was best among all experiment conditions. Both 3D building and floor maps improved the accuracy of mental representation of spatial horizontal relations within spatial layout (see Figure 5-3 and 5-4); but the 3D floor map impaired the accuracy of mental representation of spatial vertical relations within the spatial layout (see Figure 5-5 and 5-6). This impairment effect indicated that the 3D map of multilevel building should illustrate the vertical relationship between levels. These data partly supported our second hypothesis, but fully support the third hypothesis.

Further, Subjects in the transparent condition performed better than subjects in the no-map condition in terms of spatial horizontal relations (see Figure 5-3 and 5-4), indicating that the multiple views provided during elevation change can improve the mental representation of the multilevel building. In effect, subjects in the transparent condition and in the 3D building map condition showed similar performance on improving the accuracy of mental representation of the multilevel building. This finding suggested that allowing users to watch the building

layout during elevation change could be one way to assist the navigation in a multilevel building. An alternative way to provide these similar multiple views is to elevate by riding on an escalator or walking a staircase down to floor with an open view (i.e. outside of a stairwell). This alternative operation was adopted in Study 4.

It should be noted that the findings of Study 3 might not be broadly generalized. First, the experimental building had "elegant" design with the simple geometry and layout. Second, the orientation of the exocentric perspective through which the 3D floor or building map depicted the building was aligned with the forward direction in the building. This alignment might facilitate making the forward direction as the preferred orientation. Therefore, Study 4 was designed to extend the findings of Study 3 by considering these limitations.

5.2 Spatial representation and learning in a complex multilevel building

5.2.1 Purpose and hypotheses

The purpose of Study 4 was to investigate the mental representation of spatial horizontal and vertical information in the complex multilevel building (the real and virtual subway station) and the function of 3D map on influencing this mental representation. Subjects navigated a real and virtual subway station, which was also augmented with either a 3D building map, a 3D floor map, or neither. The mental representation of this building was measured by the JRD task.

Spatial learning in real and virtual environments. Partly due to the difference of the environment complexity, no consensus has been reached in the previous research in terms of the spatial learning in real versus virtual environments. When the environment is relatively simple, like only one floor layout, no significant difference is found between the spatial memories acquired from the real and virtual environments (e.g. Koh, Wiegand, Garnett, Durlach, & Shinn-Cunningham, 1999); however, when the environment is relatively complex, like the two-floor layout, spatial representation acquired in the real environment is better than that acquired in the virtual environment (e.g. Richardsonk, Montello, & Hegarty, 1999).

The same three hypotheses in Study 3 were examined again in the present study. Furthermore, we tested the spatial learning in both real and virtual environments in this study. It was expected that in the present complex environment (the subway station), subjects in the real

environment would acquire better mental representation of the environment than their counterparts in the virtual environment. However, since it was observed that the 3D map improved the mental representation of a simple multilevel building in Study 3, we further hypothesized that subjects in the virtual environment augmented with a 3D map could acquire as good spatial knowledge as those in the real environment.

To completely investigate the function of the 3D map on influencing mental representations of both simple and complex multilevel buildings, we compared the effect of the 3D map on mental representation in Study 3 and the present study. We assumed that the use of the 3D map would show a greater benefit in the complex multilevel building in the present study than in the simple multilevel building in Study 3.

5.2.2 Method

(1) Subjects. Forty undergraduate and graduate students (20 males and 20 females) from Nanyang Technological University participated in this experiment. Among them, thirty subjects volunteered to join the experiment of navigating the virtual station whereas ten subjects navigated the real station for the monetary payment. They had normal or corrected-to-normal vision. Although some subjects passed this subway station a few times, since the station is very large and busy and they just followed the passenger flow to find their way, as they stated, they seldom paid attention to the layout of the station. The subjects who ever passed this station were randomly assigned to the four groups.

(2) Materials. The hardware and operation in the virtual environment were the same as those

in Study 3. The subway station comprises three levels: the platform (B4), the middle level (B3) and the upper level (B2). Several escalators and staircases connected each level, including one long escalator directly connecting B4 and B2 and one elevator across three levels. The shape and size of each level differed. Specifically, B4 was rectangular and measured 118 m × 10 m. Both B3 and B2 were in irregular shapes: the maximum length and width of B3 was 125 and 37 meters, respectively, and the maximum length and width of B2 was 54 and 66 meters, respectively. Nine facilities were chosen as landmarks inside this station: one entrance gate, the ticket office on B2, the long escalator connecting B2 and B4, one staircase connecting B2 and B3, one escalator connecting B3 and the corridor, one escalator connecting the B3 and B4, the elevator door, one information booth and one emergency board on B4.

The 3D floor map presented the layout of each level from the viewpoint 17 meters above the level depicted, looking toward to the elevator. Figure 5-9 (a) shows the 3D floor map of B2. The 3D building map (Figure 5-9 (b)) presented the whole layout of building layout from the viewpoint 12 meters above B2; the projection of the viewpoint on B2 was 58 meters in length and 25 meters in width from the elevator door. Each level was rendered in different colors for better differentiation. Some openings were made on B2 and B3 so that subjects could see facilitates below these two levels.
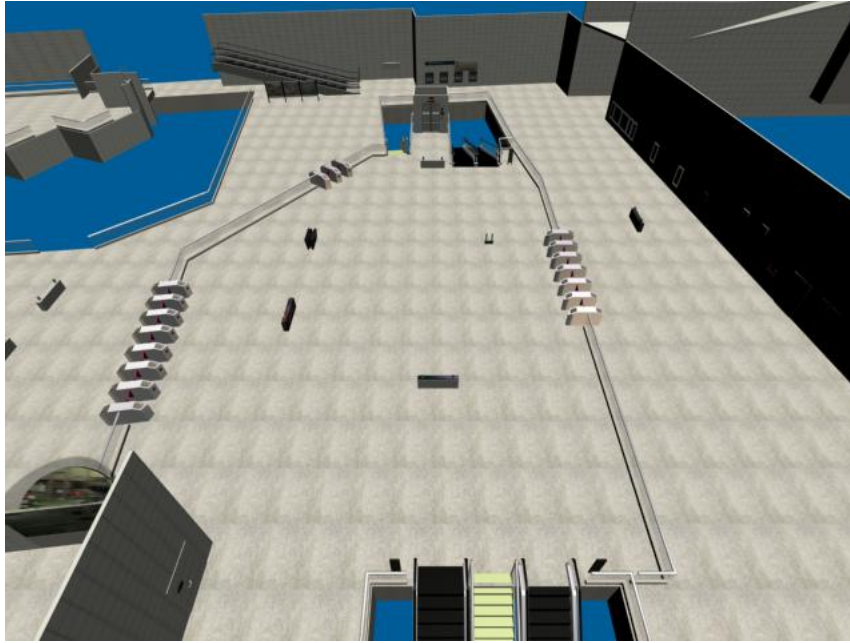
(a) The 3D floor map of B2, one of three floor maps used in the floor-map condition
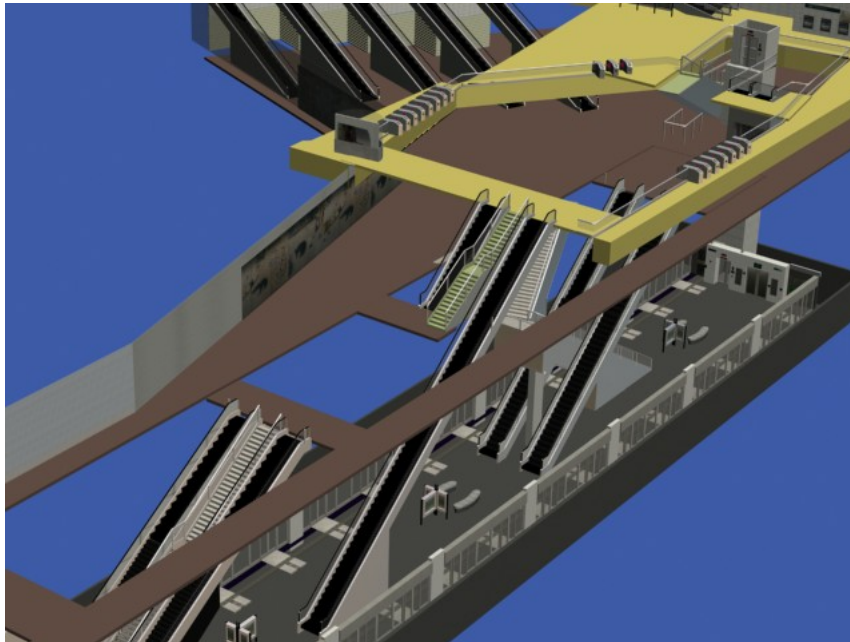
(b) The 3D building map, where some walls on floors are omitted and some opening on B2

and B3 floors are designed, so that the viewer can see objects on the lower B3 and B5 level

Figure 5-9 The 3D floor and building maps in Study 4.

(3) Design and Procedure. The design and procedure were similar to those used in Study 3, with five notable changes. First, subjects traveled between levels through the escalator and staircase by pressing the arrow keys on the keyboard to activate the movements. Subjects could observe part of the spatial layout on the coming level when walking on the escalator or staircase.

Second, the real-environment condition replaced the transparent condition in Study 3. Thus, the four navigation treatments included the no-map, 3D floor map, and 3D building map conditions in the virtual subway station, and also the real environment condition. Specifically, subjects perform the JRD task at one place near the station gate after they navigated the real station. The time to leave from station to the testing place was only around 2 minutes so that subjects did not forget the station scene in this short time.

Third, subjects were first guided to each landmark and when arriving at a landmark, they needed to relate it to its picture on the paper. After that, they returned to the starting place and were instructed to freely navigate in the station and remember the locations of the nine landmarks again. Subjects were asked to arrive on each level at least twice during the 20 minutes of free navigation. The total time was approximately 90 minutes in both virtual and real stations.

The fourth change was that only two imagined facing directions, forward and backward, were adopted in this experiment. This design was consistent with the requirement in the real station. Passengers enter the station along the forward direction—for example, facing forward before walking down the escalator; passengers leave the station along the backward direction—for

example, with their backs to the station before leaving the escalator.

The last change was that, in contrast to Study 3, the orientation of the 3D floor or building map was opposite to the forward direction in which passengers enter the station. This opposite direction was chosen to examine whether or not the orientation of 3D map could affect the preferred orientation bias acquired in the multilevel building.

5.2.3 Results

All dependent measures were subjected to an analysis of variance (ANOVA) with terms for the navigation treatment, level condition and imagined facing direction. The relative means are shown in Table 5-2.

(1) The judgment accuracy of horizontal direction. The main effect of navigation treatment on the judgment of horizontal direction was not significant. The main effect of level difference was significant, $F(4, 144) = 9.40$, $p < .01$, and as shown in Figure 5-10, the performance under the two levels down and the same level were better than those under the one level down, one level up, and two levels up. The interaction between the navigation treatment and the level difference was not significant.

The main effect of imagined facing direction was significant, $F(1, 36) = 7.63$, $p < .01$, and as shown in Figure 5-11, subjects estimated the spatial horizontal direction more accurately in the forward direction than in the backward direction. The interaction between the navigation treatment and the imagined facing direction was not significant.

Table 5-2 Mean accuracy (degree) and response time (second) of direction judgment in Study 4

Measure	Navigation treatment	Level difference							Imagined facing direction			
		Two down	One down	Same	One Up	Two Up	Total	Sig	Forward	Backward	Total	Sig
Error of horizontal angle	No map	20.47	26.94	20.64	37.03	28.83	26.78	n.s.	26.47	26.94	26.71	n.s.
	3D floor map	14.46	27.4	18.3	16.24	31.44	21.57	*	19.04	27.4	23.22	*
	3D building map	12.48	27.67	20.69	28.38	28.12	23.47	n.s.	22.78	27.67	25.22	n.s.
	Transparent	14.13	33.24	15.7	20.44	36.03	23.91	*	19.74	33.24	26.49	*
	Total	15.38	28.81	18.83	25.53	31.1			22.01	28.81		
	Sig	n.s.	n.s.	n.s.	*	n.s.			*	n.s.		
Error of vertical angle	No map	7.91	9.09	14.11	30.87	11.53	14.7	*	11.42	30.87	21.15	*
	3D floor map	11.79	11.04	13.8	27.99	14.3	15.78	*	12.8	27.99	20.4	*
	3D building map	11.32	10.2	14.24	32.14	5.79	14.74	*	11.46	32.14	21.8	*
	Transparent	14.56	10.2	13.25	29.69	5.39	14.62	*	11.45	29.69	20.57	*
	Total	11.39	10.13	13.85	30.17	9.25			11.78	30.17		
	Sig	n.s.	n.s.	n.s.	n.s.	*			n.s.	n.s.		
Response time	No map	80.5	49.85	57.13	82.05	64.2	66.75	n.s.	68.6	49.85	59.23	n.s.
	3D floor map	28.3	21.65	20.61	42.95	32.9	29.28	*	29.85	21.65	25.75	n.s.
	3D building map	54.5	27.55	24.57	47.38	31.2	37.04	*	36.31	27.55	31.93	n.s.
	Transparent	54	26.15	23.45	50.65	46.3	40.12	*	38.87	26.15	32.51	n.s.
	Total	54.33	31.3	31.45	55.76	43.65			43.41	31.3		
	Sig	n.s.	*	*	*	*			*	*		

Note—* indicates significant (<.05); n.s. indicates not significant

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Mean horizontal direction errors as a function of level difference and navigation treatment

Figure 5-10 Judgment accuracy of horizontal direction (a) in Study 4.
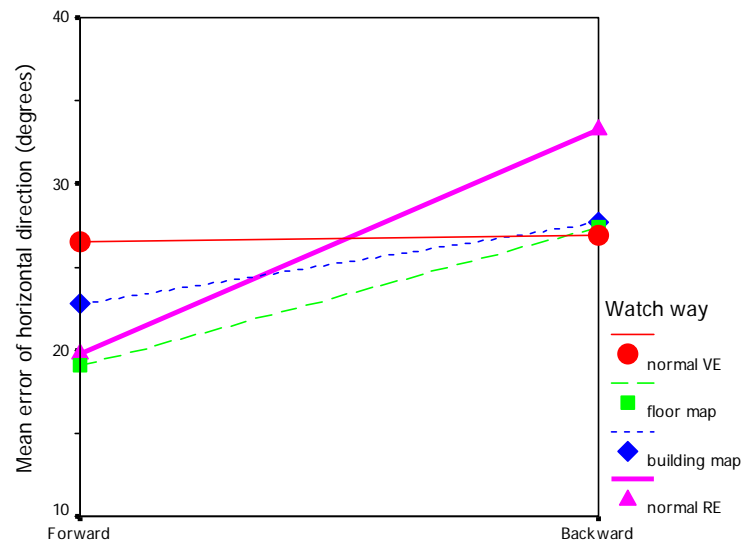
Mean horizontal direction errors as a function of imagined facing direction and navigation treatment

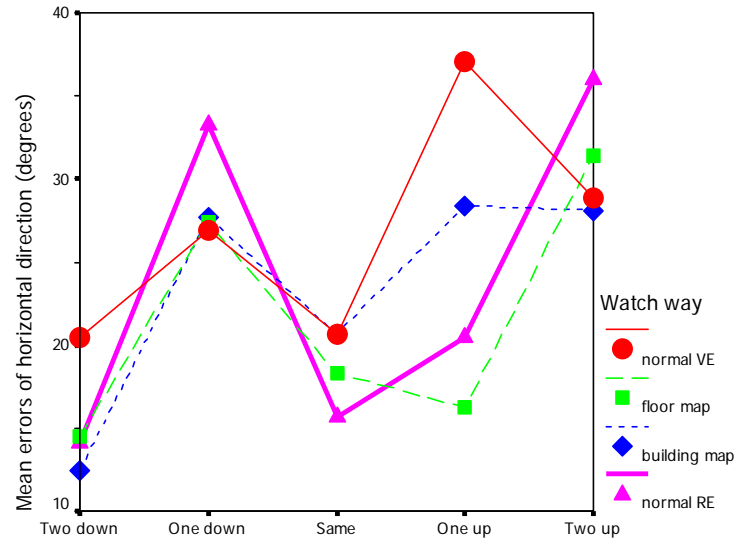Figure 5-11 Judgment accuracy of horizontal direction (b) in Study 4.

(2) The judgment accuracy of vertical direction. The main effect of navigation treatment on the judgment of vertical direction was not significant. Regarding the accuracy of judgment of the vertical direction, the main effect of level difference was significant, $F(4, 144) = 43.31$, $p < .01$, and as shown in Figure 5-12, the performance under the one level up was worse than performances under the other four level differences. The interaction between the navigation treatment and the level difference was not significant.

The main effect of imagined facing direction was again significant, $F(1, 36) = 214.62$, $p < .01$, and as shown in Figure 5-13, subjects estimated the vertical direction more accurately when imagining facing the forward direction than when imagining facing the backward direction. The interaction between the navigation treatment and the imagined facing direction was not significant.
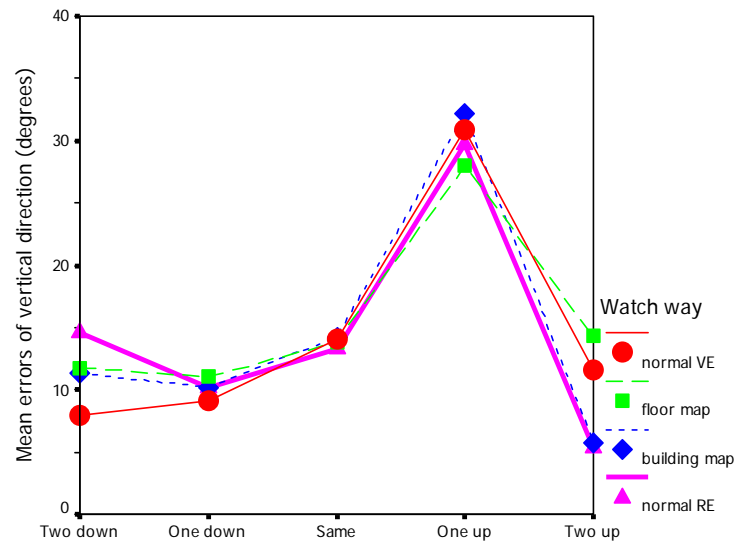
Mean absolute vertical direction errors as a function of level difference and navigation treatment.

Figure 5-12 Judgment accuracy of vertical direction (a) in Study 4.
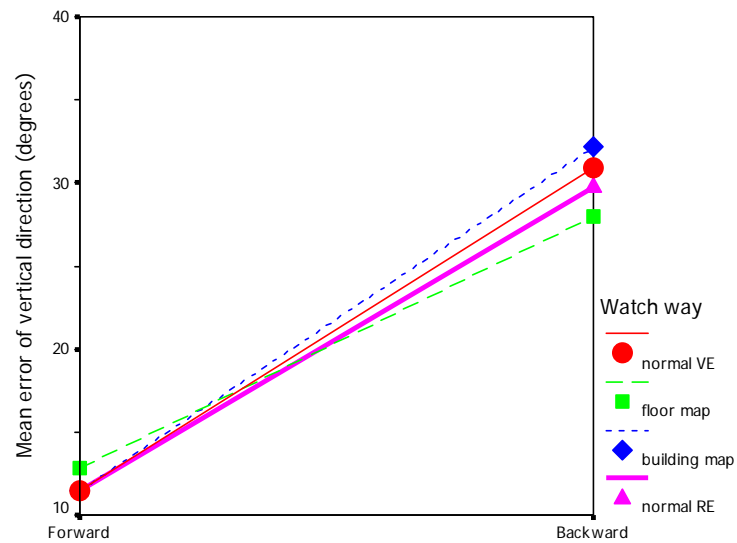
Mean absolute vertical direction errors as a function of imagined facing direction and navigation treatment

Figure 5-13 Judgment accuracy of vertical direction (b) in Study 4.

(3) Response time. As depicted in Figure 5-14, the main effect of navigation treatment was significant, $F(3, 36) = 6.90$, $p < .01$. Multiple comparisons showed that the response time was significantly longer for those trained with no map in the virtual station than for those trained under the other three conditions. The main effect of level difference was significant, $F(4, 144) = 8.82$, $p < .01$, and responses were significantly faster under the conditions of one level down and the same level than under the conditions of two levels down and one level up. The interaction between the navigation treatment and the level difference was not significant.

The main effect of imagined facing direction was also significant, $F(1, 36) = 13.94$, $p < .01$, as depicted in Figure 5-15, subjects responded faster when imagining facing the backward than the forward direction. The interaction between the navigation treatment and the imagined facing direction was not significant.
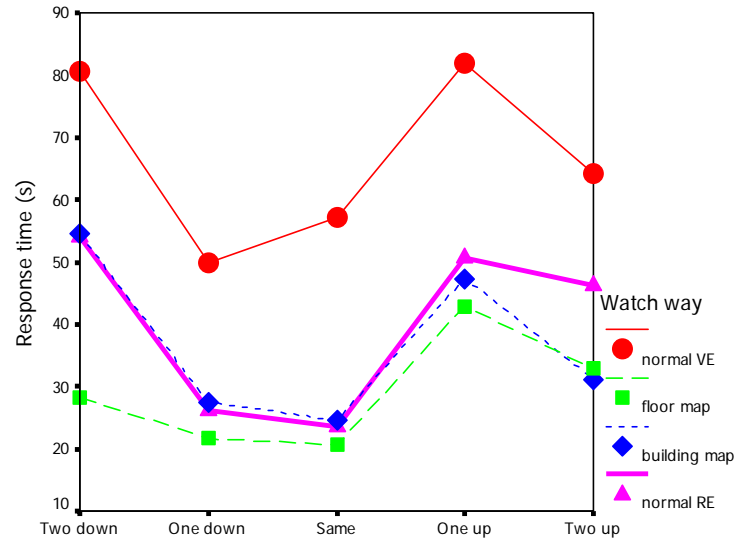
Mean response time as a function of level difference and navigation treatment.

Figure 5-14 Response time in JRD task (a) in Study 4.
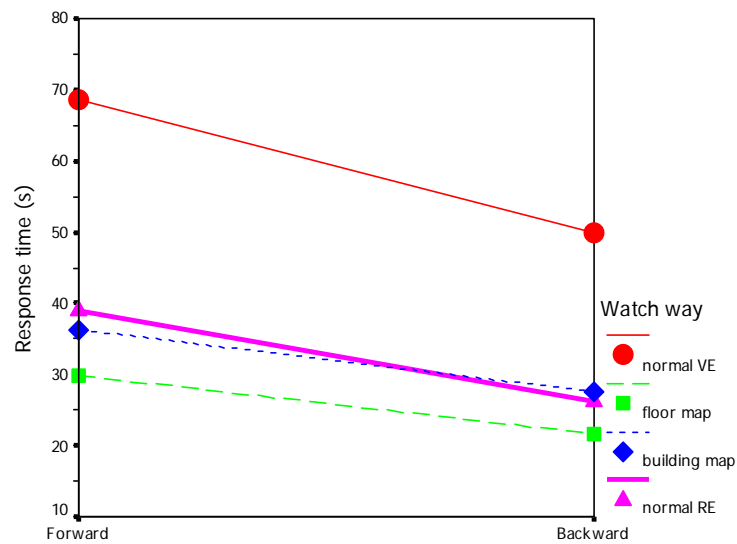
Mean response time as a function of imagined facing direction and navigation treatment.

Figure 5-15 Response time in JRD task (b) in Study 4.

5.2.4 Discussion

The results of Study 4 did not totally replicate those of Study 3. The discussion first concentrates on the similar findings in both experiments and then the main difference; it concludes with the comparison between findings in real and virtual environments.

Three findings observed in Study 4 were similar to those in Study 3. First, the vertical same-level bias was again observed in the mental representation of both virtual and real environments. Subjects estimated both the horizontal and vertical relations of objects on the same level at least as accurately as they estimated the directions of objects on different levels, and usually more so, which replicated the findings of Study 3. Second, as indicated by the angular error of vertical direction (see Figure 5-12), the downward bias in mental representation was again observed, which was also consistent with the previous research (e.g. Wilson, Foreman, Stanton, and Duffy, 2004). Third, as indicated by the judgment of both horizontal and vertical directions (see Figure 5-11 and 5-13), the forward direction was again observed as the preferred orientation in Study 4, and this also replicated the findings in the previous research (e.g. Shelton and McNamara, 1997; Sholl, 1999; Wickens, Vincow & Yeh, 2005).

In addition to the near doubling of response time in Study 4 compared to Study 3 (i.e., reflecting the influence of the added complexity), the main difference found between two experiments concerned the function of 3D map in influencing mental representation of the multilevel building in the two experiments. Compared with no map group, in Study 4 the use of 3D map increased the speed of estimating direction; in contrast, in Study 3 the use of 3D

map improved the accuracy of mental representation of the building space. One possible explanation for this difference was that the landmarks with perceptual and functional salience played a more important role than did the 3D map in shaping the mental representation of subway station in Study 4. The influence of landmarks might also explain why subjects made the relatively accurate estimation of the vertical direction of targets two levels above (see Figure 5-12). In this specific task, subjects were required to imagine standing on B4 and point to the upper entrance of the long escalator connecting B2 and B4, which could serve as a very salient landmark. In addition, the faster judgment in the backward direction than in the forward direction (see Figure 5-15) might also be due to the relatively more salient landmarks to be pointed in the backward direction.

Lastly, subjects in the real environment performed spatial task (mean response time, RT = 32.51 seconds) faster than those in VE without the map aid (mean RT =59.23 seconds), suggesting the advantage of spatial learning in the real environment over the virtual environment (Montello, Hegarty, Richardson, & Waller, 2004; Richardson, Montello, & Hegarty, 1999). However, subjects in the 3D floor and building map conditions in VE performed the same as those in the real environment. This new finding suggested that providing 3D map in the virtual environment could significantly improve the efficiency of spatial learning.

5.3 General Discussion

Both studies revealed the three biases of spatial memory   vertical same-level bias, downward bias and preferred orientation bias   after subjects navigated the two multilevel buildings augmented without the 3D map. The present two studies also demonstrated that the use of the 3D map influenced the mental representation of a multilevel building. In the simple multilevel building, the 3D map did improve the accuracy of mental representation; in the complex multilevel building, the 3D map did facilitate the time to recall object's direction. 3D building map was found the optimal aid for assisting the understanding of spatial structure in the multilevel building.

5.3.1 Mental representations of spatial horizontal and vertical information

The performance to judge the spatial horizontal and vertical directions in each study was different, especially when the reference and target objects in each question of JRD task were at different levels. The results indicated that mental representations of spatial information on the horizontal and vertical dimensions of a multilevel building were different.

5.3.1.1 Different representations in a simple multilevel building

The mental representations of spatial horizontal and vertical directions were different in Study 3 when subjects navigated in a simple multilevel building. When the mental representation was examined in terms of the level difference and the navigation treatment (learning

experience), the error of horizontal direction showed that subjects made more accurate judgments in estimating the upward direction of target rather than the downward direction (see Figure 5-3). The error of vertical direction, however, showed that the subjects made more accurate judgments in estimating the downward direction of target rather than the upward direction (see Figure 5-5), which was similar with the finding in the study of Wilson et al. (2004a). The effect of learning experience on these two mental representations was also different. Both 3D floor and building maps improved the accuracy of mental representation of spatial horizontal information among objects at different levels. The 3D floor map, however, could significantly impair the mental representation of spatial vertical information among objects at different levels.

When the mental representation was examined in terms of the imagined facing direction and the navigation treatment (learning experience), the effect of the 3D map on each mental representation was different too. The 3D map generally improved the accuracy of mental representation of spatial horizontal information (see Figure 5-4). The 3D floor map significantly impaired the mental representation of spatial vertical information (see Figure 5-6). There was, however, a common property between these two mental representations: the preferred orientations of mental representations were the same. That is, the forward direction was the preferred one in the mental representations of both spatial horizontal and vertical information in a simple multilevel building.

5.3.1.2 Different representations in a complex multilevel building

The mental representations of spatial horizontal and vertical information, when subjects

navigated the complex multilevel building in Study 4, were significantly different only when these two representations were examined in terms of the level difference and the navigation treatment (learning experience). The error of horizontal direction (see Figure 5-10) showed the significant effect of landmarks in the multilevel building on the mental representation of spatial horizontal information (Golledge, 1999); while the error of vertical direction (see Figure 5-12) generally showed that subjects made more accurate judgments of estimating the downward direction of target rather than the upward direction, although the effect of landmark on this representation was also observed.

In general, the data of Studies 3 and 4 suggested that mental representations of spatial horizontal and vertical information in multilevel building were encoded and represented with respect to different frames of reference.

5.3.2 3D map design

The implications of this research on designing 3D map for multilevel building are threefold. First, the design of the 3D map for multilevel building should include the illustration of vertical connection between levels since the single-floor 3D map can significantly impair the representation of spatial relations between levels in simple multilevel building (see Figure 5-5 and 5-6).

Second, the 3D map should preserve enough environmental fidelity (Waller, Hunt, & Knapp, 1998). It was found in Study 4 that the downward bias and the preferred orientation bias were attenuated by the salient landmarks in the complex multilevel building (see Figure 5-12 and

5-15). By preserving the fidelity of the layout, especially for those salient landmarks in the building, the 3D map can help to overcome these two biases in spatial representation.

Finally, the orientation of the 3D map should also receive attention. Although changing the orientation of the 3D map did not significantly affect the preferred orientation bias in Study 4, the alignment between the forward orientation faced by subjects in the environment and the orientation of the 3D map did facilitate the memory of object's location in Study 3. This is consistent with the forward-up equivalence used in designing You-Are-Here (YAH) map (Levine, 1982).

These implications suggest that architectural or environmental designer should articulate the information display (e.g. the building or floor map) correctly while bearing the following three questions in mind: what information should be presented, in what form, and in which direction. Simply drawing a nice display, depicting as much information as possible, or even setting the orientation of the display arbitrarily cannot efficiently help users to develop a good mental representation of a multilevel building.

Finally, it should be noted that the present study was not free of limitations. To some degree, the results of this study may lack full generalization to other virtual or real multilevel buildings because of the different spatial layout and complexity. In addition, in Study 4 subjects in the real-environment condition (the real subway station) were paid while subjects in the three virtual-environment conditions were not, and thus, subjects in the real environment might be more motivated. However, despite this constraint, the results of Study 4 indicated that the VE training with maps can be as good as the real-environment training.

Chapter 6 Conclusions and Future Work

In this research, we have obtained a lot of results about mental representations of environments. Through designing different spatial learning experiences and environmental characteristics, this research revealed the cognitive processes of how people build mental representation of spatial horizontal and vertical information in the real and virtual environments. In reconsidering these immediate results and their implications to theory and practice, we think that this research adds a further step to the area of spatial cognition in the environment. Future work is necessary in this line of research.

6.1 Contributions

Three major findings in this research revealed the underlying cognitive process of spatial representation and learning in real and virtual environments. First, mental representations of spatial horizontal and vertical information were encoded and represented with different frames of reference in mind. Second, the exocentric view provided by watching from an exocentric perspective or by studying the 3D map could facilitate the acquisition of survey knowledge in the environment. Third and lastly, the orientation-dependent property of mental representation was observed in both the 3D room environment and the multilevel building, and moreover, there were two more properties – vertical same level bias and downward bias – observed in the mental representation of the multilevel building.

6.1.1 Mental representations of spatial horizontal and vertical information

The results of this research indicated that mental representations of spatial horizontal and vertical information in the environment were different. The reason why these mental representations were different was that spatial horizontal and vertical information was encoded and represented with respect to different frames of reference in mind. It answers the first question raised from the previous research (see section 2.6.1 of Chapter 2).

Through examining the mental representation of spatial horizontal information in four studies, the results showed that environmental characteristics played a significant role in building this representation. For instance, when subjects could learn spatial layout in the 3D room environment from multiple perspectives in Study 2, the change of environmental geometry (room wall shape) significantly influence the mental representation of spatial horizontal information. Furthermore, when the complex multilevel building was considered in Study 4, the mental representation of spatial horizontal information was significantly affected by landmarks in the building.

Through examining the mental representation of spatial vertical information in four studies, the results showed that learning experiences played a significant role in building this representation. For instance, when subjects could learn spatial layout in the 3D room environment from multiple perspectives in Study 2, the more views to spatial layout (attentive vs. normal elevation) significantly improved the accuracy of mental representation of spatial vertical information. Furthermore, when the simple multilevel building was considered in

Study 3, the different 3D maps (3D building map vs. 3D floor map) provided during navigation also influenced the mental representation of spatial vertical information.

It should be noted that the orientation-dependent mental representations of spatial horizontal and vertical information were observed across all four studies in this research. In particular, the preferred orientations in two mental representations were the same with each other. Subjects generally retrieved the spatial information more accurately from a specific orientation, the one aligned with the dimension of facing direction during spatial learning or with the dimension of initial viewing direction when entering environment. It should be noted, however, that one exception was observed that the backward direction that was opposite to the facing direction (the forward direction) was the preferred direction in retrieving the spatial horizontal information in mind (see Figure 4-4) in Study 1. The result indicated that different frames of reference could contribute to build mental representations which share the same property.

6.1.2 Acquisition of survey knowledge

The results of Studies 1 and 2 showed the function of exocentric view on the acquisition of survey knowledge in 3D room environments. Generally, the results suggested that the exocentric view acquired from an exocentric perspective facilitated the acquisition of survey knowledge in the 3D room environment. For instance, when the spatial layout was learned from one egocentric perspective and one exocentric perspective in Study 1, the mental representation of spatial horizontal information was not influenced at all by the environmental geometry and the learning experience (the sequence of experiencing two perspectives). The

results of Study 2 suggested that subjects with more exocentric views (in attentive-elevation condition) could better acquire survey knowledge in the 3D room environment than their counterparts with less exocentric views (in normal-elevation condition). These findings answer the question raised from previous research about spatial learning from both egocentric and exocentric perspectives (see section 2.6.2 of Chapter 2).

The results of Studies 3 and 4 showed the function of a 3D map on the acquisition of survey knowledge in the multilevel building. When the multilevel building was relatively simple in Study 3, the 3D map improved the accuracy of mental representation of this simple multilevel building. In particular, the 3D building map which rendered spatial structure into one medium was recommended to acquire survey knowledge in the simple multilevel building. When the building was relatively complex, the 3D map only facilitated the time to retrieve spatial information. These findings answer the research questions raised from previous research about the 3D map (see section 2.6.3 of Chapter 2).

6.1.3 Property of mental representation

As discussed above, the orientation-dependent mental representations of spatial horizontal and vertical information were observed across four studies. The preferred orientation bias is caused by this property of mental representation. Preferred orientation is a strong bias in human memory system, regardless of the learning experience (e.g. two and multiple perspectives in Studies 1 and 2, the use of 3D map in Studies 3 and 4) and the environmental characteristics (e.g. the environmental geometry in Studies 1 and 2, the environmental complexity in Studies 3 and 4). The findings answer the research question about the property

of mental representation acquired from spatial learning from both egocentric and exocentric perspectives (see section 2.6.2 of Chapter 2).

Two other biases, the same-level bias and the downward bias, were found in multilevel buildings in Studies 3 and 4. Subjects generally made more accurate judgment to spatial objects on the same level, rather than on different levels. Meanwhile, subjects generally made more accurate judgments in the downward direction than in the upward direction. The findings about three biases in mental representation of multilevel building answer the research questions raised in previous research (see section 2.6.4 of Chapter 2). It should be noted, however, that downward bias could be affected by the landmarks in the multilevel building (see section 5.3.4 of Chapter 5).

6.2 Limitations

A thorough understanding of the mechanism of how people process spatial information cognitively in the environment is not a realistic goal at this point. This research is subject to the following limitations.

This research focused on mental representations acquired in two specific environments, a 3D room environment and a multilevel building, and these environments were mainly simulated on the computer.

Visual information was the main source of spatial learning in the present research. This research did not consider the effect of other models of perception on the mental representation

of spatial layout, for example the body sense (Berthoz & Viaud-Delmon, 1999) and the auditory sensation.

The simulation of the virtual building was restricted to a small number of physical input and output devices that were in common use. For the display of VE, the first two studies used a head-mounted display (HMD) and the last two studies used a computer screen. On the input side, subjects activated movement in the virtual environment by pushing the arrow keys on the keyboard.

Finally, we focused on the single-user system. That is, only one subject was allowed to join the experiment in one trial. One individual's spatial cognition of environment can be affected by others' behaviors in the same environment. However, we must know more about the simple case in which only one individual is in the building.

6.3 Future work

There are a multitude of topics to be explored in the area of spatial cognition in real and virtual environments. In particular, four areas directly related to this research would be extremely useful.

6.3.1 More ways of elevation

We considered some ways of elevation in this research. For instance, we simulated the elevation in a lift in Study 3 and elevation along an escalator in Study 4. There are many other

ways of elevation in a building, one of which is to walk on a staircase to another level. Movement on a staircase would be complex. First, people would turn their orientations on staircase. Second, people may not observe the outside layout because of the closed wall of stairwell.

This relatively complex elevation can impair mental representation and wayfinding performance in multilevel buildings. Richardson, Montello and Hegarty (1999) found that subjects pointed to the objects less accurately between levels than within a level, and attributed this inferior performance to the distortion to represent the close stairwell space. Disorientation is observed after elevation along the staircase (Soeda, Kushiyama, & Ohno, 1997). Since the staircase is one important component of a multilevel building, we need to explore how the elevation by walking a staircase affects the mental representation in the future study.

6.3.2 Wayfinding in a multilevel building

We assessed the mental representation of multilevel buildings in the present research. The data demonstrated that people can represent both spatial horizontal and vertical relations within a 3D spatial structure in this building. However, we have not tested how people perform the wayfinding task based on their mental representation. The study of wayfinding in the multilevel building has significant application in our daily life. One example, mainly for the safety purpose, is to assist passenger's navigation in a subway station. Passengers in a subway station perform the wayfinding task to arrive at the destination. The correct mental representation of the whole station, however, is the key for wayfinding inside the station. Our

research has provided some knowledge background to investigate wayfinding in a subway station.

6.3.3 More design guidelines for the 3D map

The 3D map is useful for the acquisition of survey knowledge in real and virtual environments. Beside the implications to design 3D map introduced in section 5.3.2 of Chapter 5, our research raises three concerns to design an effective 3D map. The first concern is to select optimal parameters, such as the position of viewpoint and the field of view, of 3D map. McGreevy and Ellis (1986) proposed a geometrical model to define some parameters of the 3D map.

Second, some design principles for the 2D map can also be adequate for the 3D map. For instance, principles for designing the You-Are-Here (YAH) map (Levine, 1982; Levine, Marchon, & Hanley, 1984), such as the forward-up equivalence, can help to set up the position of 3D map in the multilevel building. An alternative way is to label the observer's orientation in front of the 3D map, similar to the arrow labeled in YAH map. This can facilitate the incorporation between the egocentric orientation and the exocentric overview so that people can easily maintain their orientation in a building.

Finally, to enhance the training in the virtual multilevel building, the 3D map should always show the navigator's position in the building, which can improve the internal navigation (Darken & Sibert, 1996). This design enables the navigator to coordinate the map feature with the facing building structure more effectively and quickly, thereby maintaining a high spatial

awareness within the building.

6.3.4 Transfer of spatial knowledge from virtual to real environments

Training requires people to be able to transfer spatial knowledge acquired in a VE to a real-world situation. This is one primary objective of research in VE. As an example, the virtual fire-fighting simulator trains firefighters to move through the spatial layout of building before they enter the real environment to put out an actual fire (Bliss & Tidwell, 1997).

Previous research has investigated the transfer of spatial knowledge from the virtual to real buildings. But most studies focus on the transfer of spatial knowledge acquired from the planar layout on one level of the building. Few studies investigate the transfer of spatial knowledge acquired from navigating in the multilevel building. Spatial knowledge acquired in the multilevel building is more complex than that acquired in the planar layout. People in the VE training should learn not only the spatial relative direction on the horizontal plane but also the spatial relative direction along the vertical dimension of the multilevel building. This brings more challenges to the transfer of spatial knowledge. Three fundamental questions should be answered at the outset: What task is useful for acquiring the spatial knowledge of the multilevel building? What training procedure should be used to learn the 3D building structure? What criteria should be adapted to assess spatial knowledge, especially spatial vertical relations?

One minor challenge is about using a 3D map in this training. The 3D map is observed in this research to improve spatial learning in the multilevel building. However, the application of a

3D map to guide spatial navigation in the real building is still rare. Rendering the 3D map on a personal digital assistant (PDA) or other mobile electronics has not been realized well until now. Therefore, if the navigation aid (a 3D map) is not available in a real building, it is still difficult to determine the effect of the training in VE on improving the real-world performance.

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Appendix A: Study 1 consent form

Title of Project:
Spatial Learning of Room-sized Space From Two Viewpoints
Investigator:
Luo Zhiqiang

I. Purpose of the Research
The purpose of this research is to investigate how people learn the spatial layout in the room-sized space from two viewpoints.

II. Procedures
There are total three phases in the formal experiment:
Pretest phase. Participants should firstly take a memory test by remembering 9 objects printed on a paper.
Learning phase. Participants will observe the virtual room from two viewpoints by wearing a HMD. The time for observation from each viewpoint is 2 minutes. Before observing the virtual room, you will take some trial to adapt virtual scene on HMD.
Test phase. Participants will use the laser pointer to label the direction of object observed in the virtual scene.

III. Risks
There are minimal risks to you in this study.

IV. Extent of Anonymity and Confidentiality
You will be identified only by a subject number in data analysis. No written results of this study will be traceable to a participant by name.

V. Compensation
You will be compensated for your participation for $10.

VI. Freedom to Withdraw
You are free to withdraw from this study at any time without penalty.

VII. Subject's Responsibilities
I agree to undergo the procedures of this experiment as described above.

IX . Subject's Permission
I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project. A copy of this Informed Consent Form will be provided.

_____   _____
Signature   Date
If you have any questions about this research or its conduct, you may contact:
Luo Zhiqiang   (+65) 6790-5894   Email: peterluo@pmail.ntu.edu.sg

Appendix B: Study 2 consent form

Title of Project:
Spatial Learning of Room-sized Space From Multiple Viewpoints
Investigator:
Luo Zhiqiang

I. Purpose of the Research
The purpose of this research is to investigate how people learn the spatial layout in the room-sized space.

II. Procedures
There are total three phases in the formal experiment:
Pretest phase. Participants should firstly take a memory test by remembering 9 objects printed on a paper.
Learning phase. Participants will observe the virtual room by wearing a HMD. There will be simulated elevation process. Before elevation, participants will spend 2 minutes to observe the virtual room and then start elevation in virtual room. Before observing the virtual room, you will take some trial to adapt virtual scene on HMD.
Test phase. Participants will use the laser pointer to label the direction of object observed in the virtual scene.

III. Risks
There are minimal risks to you in this study.

IV. Extent of Anonymity and Confidentiality
You will be identified only by a subject number in data analysis. No written results of this study will be traceable to a participant by name.

V. Compensation
You will be compensated for your participation for $10.

VI. Freedom to Withdraw
You are free to withdraw from this study at any time without penalty.

VII. Subject's Responsibilities
I agree to undergo the procedures of this experiment as described above.

IX . Subject's Permission
I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project. A copy of this Informed Consent Form will be provided.

_____   _____
Signature   Date
If you have any questions about this research or its conduct, you may contact:
Luo Zhiqiang   (+65) 6790-5894   Email: peterluo@pmail.ntu.edu.sg

Appendix C: Study 3 consent form

Title of Project:
Representation of Spatial Layouts in a Three-Level Virtual Building
Investigator:
Luo Zhiqiang

I. Purpose of the Research
The purpose of this research is to investigate how people memorize the spatial layout in the 3-level virtual building.

II. Procedures
There are total three phases in the formal experiment:
Pretest phase. Participants should firstly take a simple memory test.
Learning phase. Participants will navigate the virtual building simulated on the computer by operating the keyboard and the mouse. During the navigation, participants need to fulfill three tasks. First, they need to walk into each level of building at least three times. Second, they need to use the mouth to click objects required. Third, they need to remember the location of each object in this building.
Test phase. Participants will use the laser pointer to label the direction of object observed in the virtual scene, then estimate the distance between two of objects.

III. Risks
There are minimal risks to you in this study.

IV. Extent of Anonymity and Confidentiality
You will be identified only by a subject number in data analysis. No written results of this study will be traceable to a participant by name.

V. Compensation
You will be compensated for your participation for $10.

VI. Freedom to Withdraw
You are free to withdraw from this study at any time without penalty.

VII . Subject's Responsibilities
I voluntarily agree to participate in this study. I agree to undergo the procedures of this experiment as described above.

IX . Subject's Permission
I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project. A copy of this Informed Consent Form will be provided.

_____   _____
Signature   Date
If you have any questions about this research or its conduct, you may contact:
Luo Zhiqiang   (+65) 6790-5894   Email: peterluo@pmail.ntu.edu.sg

Appendix D: Study 4 consent form

Title of Project:
Representation of Spatial Layouts in a subway Station
Investigator:
Luo Zhiqiang

I. Purpose of the Research
The purpose of this research is to investigate how people memorize the spatial layout in the virtual subway station.

II. Procedures
There are total three phases in the formal experiment:
Pretest phase. Participants should firstly take a simple memory test.
Learning phase. Participants will navigate the virtual MRT station simulated on the computer by operating the keyboard and the mouse. During the navigation, participants need to fulfill three tasks. First, they need to walk into each level of station at least one time. Second, they need to use the mouth to click landmarks required. Third, they need to remember the location of landmark in the station.
Test phase. Participants will use the laser pointer to label the direction of landmark observed in the virtual scene, then estimate the distance between two of landmarks.

III. Risks
There are minimal risks to you in this study.

IV. Extent of Anonymity and Confidentiality
You will be identified only by a subject number in data analysis. No written results of this study will be traceable to a participant by name.

V. Freedom to Withdraw
You are free to withdraw from this study at any time without penalty.

VI . Subject's Responsibilities
I voluntarily agree to participate in this study. I agree to undergo the procedures of this experiment as described above.

VII . Subject's Permission
I have read and understand the Informed Consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project. A copy of this Informed Consent Form will be provided.

_____   _____
Signature   Date
If you have any questions about this research or its conduct, you may contact:
Luo Zhiqiang   (+65) 6790-5894   Email: peterluo@pmail.ntu.edu.sg

Appendix E: Memory test materials

Appendix F: Post Questionnaire in Studies 1 and 2

POST-EXPERIMENT QUESTIONNAIRE

1. Could you describe in brief what strategy you use to remember the spatial layout?

_____
_____
_____
_____
_____

2. How do you figure out the direction of target?

_____
_____
_____
_____
_____
_____

3. What do you think is most difficult to do in the experiment?

_____
_____
_____
_____
_____
_____
_____

4. Do you have any comments on this experiment?

_____
_____
_____
_____
_____

Thank you for your participation.

Appendix G: Post Questionnaire in Study 3

POST-EXPERIMENT QUESTIONNAIRE

1. Could you describe in brief what strategy you use to remember the spatial layout in each level and the whole building?

    _____
    _____
    _____
    _____

2. How do you figure out the direction of pointed target?

    _____
    _____
    _____

3. How do you figure out the distance between the faced objects and the pointed target?

    _____
    _____
    _____
    _____
    _____

4. What do you think is most difficult to do in the experiment?

    _____
    _____
    _____
    _____
    _____

5. Do you have any comments on this experiment? For example, the design of environment, the operation of input device, the test, and so on.

    _____
    _____
    _____

Thank you for your participation.

Appendix H: Post Questionnaire in Study 4

POST-EXPERIMENT QUESTIONNAIRE

1. Could you describe in brief what strategy you use to remember the spatial layout in each level and the whole station?
   _____
   _____
   _____
   _____
   _____

2. How do you figure out the direction of pointed target?
   _____
   _____
   _____
   _____

3. How do you figure out the distance between the faced objects and the pointed target?
   _____
   _____
   _____
   _____

4. What do you think is most difficult to do in the experiment? E.g. horizontal direction, vertical direction, distance, and so on
   _____
   _____
   _____
   _____

5. Do you have any comments on this experiment? For example, the design of environment, the operation of input device, the test, and so on.
   _____
   _____
   _____

Thank you for your participation