Investigating Aging Effect on Usage of Geometry and Feature in Virtual Reality Environment

by

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Abstract

Aging changes our daily life; older people generally have difficulty in remembering and recalling information. Such decline usually includes re-orientation and spatial navigation skills as well. Recent development of virtual reality (VR) environments enables us to design navigational tasks to assess the plausible age-related changes. In this thesis, the use of geometrical and featural cues for navigation in a VR environment has been investigated through a series of experiments between young and older adults.

First, reorientation paradigm was employed to evaluate ecological validity of an immersive VR environment by comparing young participants' choice of spatial cues between real and virtual environments. The findings suggest that although VR environments do not provide a spatial perception fully matched to the one in a real environment, while the VR environments are ecologically valid for such experiments. Second, an environment including a matrix of hallways was designed to investigate the use of geometry and featural cues among young and older adults in their navigational strategy. The results showed a general tendency of inconsistent navigation patterns among the older adults, namely when they were placed in a novel location and asked to find a target location that they were trained to navigate. Such inconsistency was not seen in young group. Third, a serious game, designed for iPads, was employed to assess the use of the spatial cues in a non-immersive VR setup. In particular, the feasibility of the game for training the utilization of geometrical cues was investigated. The difference between the young and old groups of participants was found not to be statistically significant in the first few sessions of the game. However, it

was shown that the older group learned to use geometrical cues to navigate with less frequency of mistakes; this suggests it is possible to improve spatial cognition by a serious game design.

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Dedication

To my parents, Takafumi and Yumi Kimura.

Contribution of Authors

This is a sandwich style thesis, consisting of three individual manuscripts. At the time of writing (as of April 2020), two of the manuscripts have been published in a peer reviewed Journal (Chapters 2 and 3), and one of the manuscripts is to be submitted to a peer reviewed Journal (Chapter 4).

Mr. Kazushige Kimura was the first author of the all manuscripts presented in this thesis. Mr. Kazushige Kimura’s contribution to this thesis includes forming research question, design experiments, collecting data, data analysis, writing the manuscripts, and responding to reviewer’s comment. Dr. Byagowi and Mr. Paul White contributed to the hardware and software design, respectively in the studies presented in Chapter 2 and 3; Ms. Ashley Olsen contributed to a part of collecting and organizing data, namely in real environment presented in Chapter 2; Dr. Xikui Wang contributed to the design of statistical analysis in Chapter 2; Dr. James Reichert and Dr. Debbie Kelly contributed to the design of the studies and to writing the manuscripts; Dr. Zahra Moussavi contributed to forming the research questions, to the design of the studies and to writing the manuscripts.

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List of Abbreviations

VR	Virtual Reality
VRN	Virtual Reality Navigation
HMD	Head Mounted Display
CAVE	Cave Automatic Virtual Environment
MoCA	Montreal Cognitive Assessment
APP	Application
MRI	Magnetic Resonance Imaging

Chapter I. Introduction

1-1. Motivation

Our ability to Navigate is a crucial skill in our daily life; however, the mechanisms involved in navigation are not clear. During a successful visually guided navigation, cues within an environment should be encoded and recalled. A reorientation paradigm to investigate the process of recovering orientation, can demonstrate the flexibility of humans in using geometrical and featural cues. The usage of the cues is sensitive to the design of the environments; for example, the environment's size and platforms presenting an environment (i.e., real versus virtual) may change the reliance of the type of cues used to reorient. Recent technology advances permit lightweight and portable virtual reality (VR) headsets that immerse humans much better than older VR setups using just a computer monitor screen; thus, there are claims to these provide better replacement for experiments run in real physical environments. However, can we use the cutting-edge immersive VR setups as a replacement of real environment for human spatial cognition study? The ecological validity of such an immersive VR setup is investigated in this thesis (Chapter 2).

Despite many researches on animals and humans on the usage of spatial cues [1-13], the use of geometrical and featural cues has not been investigated in large-scale environments; the reasons are mainly because geometry manipulation within such an environment is not feasible in real environments, and also the 3D desktop VR environments without participants experiencing physical motion do not provide a comparable experience to that of real life. We explore this problem in this thesis by designing an immersive VR maze environment (Chapter 3).

Investigating different mechanisms for navigation by different age groups has been a topic of interest [14-19] because aging impacts memory, executive functions, and spatial cognition; thus, navigation ability is also affected. In this thesis, we question how the usage of geometrical and featural cues are affected by healthy aging and whether older adults can be trained to use more geometric cues while navigating towards a target as it seems geometry usage is more affected by aging [20]. Chapters 3 and 4 address these questions.

1-2. Orientation studies

For a successful navigation, encoding and retrieval of spatial cues within an environment is critical. The spatial cues available during a visually guided navigation can be divided into either geometry or feature. The former includes direction and distance information (e.g., the length of a wall), whereas the latter includes non-metric information (e.g., the specific color pattern of a wall). Reorientation paradigm, which was first employed by Cheng [1], manipulates geometry and feature after learning a goal location within an environment to investigate the use of geometric and featural properties during the process of orientation recovery (i.e., reorientation).

Unlike other well-known paradigms such as Morris Water Maze [21-23], Y-maze [24, 25] and radio-arm maze [26, 27], the reorientation paradigm does not investigate abilities to use allocentric (i.e., objects-oriented) and egocentric (i.e., self-oriented) navigation strategies

[28]. However, the reorientation paradigm is to segregate the use of geometry and feature using a small simple room environment [2-4].

Among the studies employing the reorientation paradigm, several animals such as birds (pigeons [5, 29, 30], chickens [31-34], crow [6, 7, 35]), fish [36-38], bees [8, 39, 40], and monkeys [41] were found to encode feature besides geometry. To further investigate which of the cues was preferred, cue conflict test, during which featural cue was located at a geometrically incorrect location, was introduced. While birds and bees use featural cues predominantly over geometrical cues [7, 8], the preference of them depends on the design of training trials and size of tested environment with a tendency of the preference towards featural cues when the environment is large [5, 6, 29, 35, 37]. These findings demonstrate flexibility of geometrical and featural cue usage in birds and fishes. Furthermore, a study used 3xTg-AD transgenic mice with impairment in distal cue usage [9], to investigate the effect of neurological disorders on reorientation task [42], and showed that the 3xTg-AD transgenic mice did not prefer to use featural cue when the geometrical and featural cues were presented in a conflict manner.

Humans reorientation ability was also tested with the same paradigm as described above. The results show human children use geometrical cues solely and similar to rats, whereas human adults use both geometrical and featural cues [2, 10]. Perhaps the human brain, by nature, has an ability to use geometrical cues, and learns to integrate featural cues. The ability to integrate featural cues arises around age 5 years, and human adults show a greater amount of flexibility in the use of featural and geometrical cues during reorientation task [43].

The idea of flexibility in choosing geometrical or featural cues is supported by the dependence of the weight between the geometrical and featural cues on the experimental setup in each study; for example, the geometrical cues were less weighted than the featural cues in a 2D virtual environment [11], whereas both were used equally in a 3D virtual environment [12]. The weight also depended on the design of the environment used during training sessions [44], which was also found in some animal studies on birds [5, 6, 29, 35]. In addition, the preference of the cues to reorient was altered by human adults when the size of the environment changed; the geometrical cues were preferred in a 4x6x6 feet environment, whereas the featural cues was preferred in an 8x12x8 feet environment [13, 45]. Such preference was observed in animal (i.e. fishes and rats) studies as well [37, 46]. Furthermore, acquisition of the global and local geometries was compared in two different scenarios: field of views of 50 and 100 degrees in diagonal direction were employed to present a virtual environment; the results showed acquisition of the global geometry was enhanced in the latter environment [47]. The paradigm was also extended to non-visual input such as audio or texture of objects placed within an environment, and human showed abilities to reorient using such non-visual cues [48, 49].

To summarise, the use of spatial cues among human adults is flexible and dependent on the environment's platform, dimension and the field of view of the setup. Based on animal and human studies two theories, called *geometry module* and *adaptive combination* theories, have been proposed to explain the mechanism involved during reorientation [1, 50-52]. The geometry module theory suggests that animals possesses an isolated module which encodes 3D surfaces of an environment selectively, which is used as a primary source of telling a location within the environment. This theory is supported by the findings in rats and human children that exhibited rotational error (i.e., choosing a corner which is diagonal of the correct corner), while the featural itself should have allowed the subjects to identify the target's location. The adaptive combination theory suggests that the preference of the cues used for target finding depends on previous experiences, and this preference can change in different environments. This idea is supported by findings that geometry was used more often in a smaller environment while feature was used more often in a larger environment [13, 37, 45, 46]. In natural scenes, small objects such as rocks are movable such that they do not serve as reliable cues; in this case, geometry can be used more often than the featural cues (i.e., the small objects). By contrast, large objects such as mountains that do not move can be served as reliable cues. In that case, featural cues are used more often than the geometrical cues of the environment. While those two theories have been widely discussed, findings of the flexible usage of the spatial cues suggest that the reorientation paradigm can be used as an evaluation tool in terms of spatial perception of an immersive VR setup, using a real environment setup as a reference. The choice of the cues should be matched between the two setups when they provide similar perception.

1-3. VR platforms for human navigation study

Recent technology advances have increased the number of applications to investigate human spatial cognition using VR platforms, including 2D, 3D non-interactive, 3D interactive and immersive VR setups. For example, 2D and 3D non-interactive VRs have been used for picture sorting (object recognition) task and reorientation task with top-view perspectives [11, 12, 53]. However, the advantages of using VR technology to study spatial cognition are only relevant if the processes involved in virtual navigation are similar enough to those used in real navigation that accurate inferences about spatial behavior can be drawn.

The major limitation of the 2D and 3D non-interactive VRs is that navigation in a real life cannot be investigated as participants are not allowed to move through the environment. By contrast, interactive 3D desktop VRs allow participants to move continuously within the environment, providing an experience similar to that in real life. Nevertheless, lack of physical movement while moving within a VR environment can result in sensation discrepancy between vision, vestibular and sensory responses, which can cause motion sickness during VR experiments in some individuals [54]. The importance of vestibular system is supported in animal studies; it was shown vestibular lesioned rats had impaired ability to return to an origin, longer latency and frequent errors to find a trained location in radio arm maze [27]. Also, human studies showed vestibular and proprioceptive input facilitated to remember the location of objects [55] and perform wayfinding task with a higher accuracy [56]. In one of the path-integration tasks, participants followed two sides of a triangle and were asked to complete another side (i.e., to return to an origin) [57]. The results of a study employing such task suggest humans predominantly rely on body senses to navigate [58]. Thus, employing an immersive VR setup that provides physical movement is crucial for navigation studies.

To date, two approaches have been widely used to display virtual environments in immersive VR setups: one is Cave Automated Virtual Environment (CAVE) [59, 60] and the other is Head Mounted Display (HMD) [61-63]. The former is composed of several screens, projectors and glasses that participants wear during an experiment. A group of projectors show images for the right and left eyes alternatively, and the glasses selectively show the images synced with the projector. The latter, on the other hand, looks through a goggle that display two images the right and left eyes. One of the early HMDs has a very low resolution of 640x480 with a field of view of 60 degrees in horizontal and 40 degrees in vertical axis [62]. Another commonly used HMD is NVIS nVisor ST60 with a better resolution of 1280x1024, but a field of view of 47 degrees in horizontal and around 40 degrees in vertical axes; this is considerably narrow compared to the field view of our vision [64, 65].

An HMD with a wider field of view was released by Oculus; the first development kit, called Oculus Rift DK1, has 640x800 resolution and the field of view of 110 degrees in horizontal axis [66, 67]. The successor of Oculus Rift DK1, called Oculus Rift DK2, has an improved resolution of 960x1080 per eye, and the field of view of 100 degrees in diagonal direction [68]. Compared to previous generation of HMDs, Oculus Rift DK1 and DK2 allow participants to be more immersed in a virtual environment; implying the difference between virtual and natural environments is minimized in terms of vision.

Despite an immersive VR setup employing an HMD with physical motion allows simulating real-world environment during a navigation, perception in such a VR setup does not always agree with the perception in a real-world; such disagreement is one the limitation of experiments in VR environment. Thus, the ecological validity of a VR setup, whether generalization of findings in the VR setup to those in real domain, should be addressed. Comparing results of VR setup to those of real-world allows to evaluate ecological validity, and investigate the limitation of the setup. Such comparison also allows to discuss expected results if an experiment was conduced in a real environment, and would bridge between findings in the immersive VR setups and in real environment. In the study presented in Chapter 2 compares humans' reorientation performance between an immersive VR environment to a real environment using the reorientation paradigm to evaluate the spatial perception provided in the immersive VR setup.

Another limitation of VR setups is motion sickness, which has been reported in several studies [69, 70]. During the exposure to VR environments, some participants show sickness symptoms similar to carsickness and seasickness. Although several theories have been suggested to describe the cause of the cyber sickness, the exact cause has not yet been found. If a VR setup causes motion sickness, the ecological validity of such a VR setup is low. In other words, it cannot replace a real environment setup, then one may question how the spatial perception in the VR setup is comparable to that in a real environment. Therefore, it is important to investigate to what extent one's performance in a real environment would be different from that in its replica in VR environment, and whether the outcomes are comparable. This is one of the objectives of this thesis.

VR environments have been widely used in navigation studies as VR environments provide advantages compared to the real environment. Unlike the experiments in real environments, VR environments ensures consistency of the environment and greater flexibilities, which is crucial for research purpose. Examples of navigational studies employing VR environments include route-learning task in a complex maze [71-73], an analogue of the Morris Water

Maze [21-23], an analogue of radio arm maze task [26], learning a VR city environment [74-77], and wayfinding [78, 79]. These studies provide an insight of encoding spatial information, however, navigation patterns when geometry and features were manipulated in an environment that is larger than environment employed in the reorientation paradigm has not been investigated. Such investigation can reveal what information is used during navigation without being disoriented. Manipulating a real environment is not feasible unless the environment is a small room that is employed in the reorientation studies; investigating the use of geometry and feature in a large environment requires a virtual environment. Thus, we employed VR designs to investigate the research questions of this thesis.

1-4. Human aging decline during navigation

Aging decline in navigation performance has been reported in various studies. For example, use of allocentric reference frames declines selectively by aging [24, 14, 15]. Aging decline was also found, when spatial knowledge was examined by measuring the duration and distance traveled during a complex-maze route-learning task, results showed more deviations from the correct route by older (age: 65-91 years) adults compared to younger adults (age: 20-45 years) [16]. Similar findings were reported using a computerized version of the Morris Water Maze task [21] whereby compared to young adults (age: 20-29 years, mean 22.2 years), older participants (age: 60-84 years, mean 73.7 years) spent less total time, and devoted a smaller proportion of the traversed path inside the correct quadrant [17]. In another study [18], younger (age: 21-33 years, mean 24.3 years) participants were more able to employ a novel shortcut through a virtual reality (VR) city environment than older (age: 62-86 years, mean 70.1 years) participants. It should be noted that the use of a novel shortcut is considered to be the hallmark measure of a complex mental allocentric map complete with landmarks [19]. Generally speaking, older adults tend to be less efficient during navigational tasks than their younger counterparts; a difference that can often be traced to older adults being less effective at integrating distal landmarks into a stable spatial framework when learning new environments [80-91]. In the above-mentioned studies, however, encoding of geometry and feature has not investigated. Therefore, in the study presented in Chapter 3, grids of hallways were employed as the environment; that allowed young and older adults to learn a predetermined route. Once they could find a target without aid, the environments were manipulated to compare navigation strategies between the two age groups.

The older participants (50-86 years old) could distinguish the objects they observed during a navigational task from the objects they did not observe [92], however, not all of the older adults remembered the geometrical component of the environment. Another study suggested older adults preferred to use featural cues [93]; however, which of the non-geometrical cues was preferred most, and whether the older adults could learn to integrate the geometrical cues could not be answered clearly by that study. A study using a maze experiment showed that the participants remembered the landmarks placed at decision making points (e.g. an intersection to make a turn) better than those placed at non-decision making points (e.g. between intersections) [94]. Moreover, older adults made more errors than young adults during their search for the target's location in a landmark-less environment [20]. Thus, the study presented in Chapter 4 employs serious game framework to investigate learning process of geometry integration while featural cues were removed one by one.

1-5. Objectives

The goal of this study is to investigate the use of geometrical and featural cues during navigation in VR environments, and in particular investigate the plausible differences between young and older adults' performances in their usage of spatial cues. Although experiments using VR environments can be designed without any comparison with real environment, findings in such VR environments do not always reflect our behaviours in the real life. As our scope is human's navigation which occurs in our real life, validating spatial perceptions in a VR environment is important; thus, comparisons between VR and real environments is necessary. Such comparison facilitates to acquire an insight of what would happen when we replicate the experiment in a real environment; evaluating ecological validity of the VR setup should be performed first. Thus, an immersive VR setup was evaluated using reorientation paradigm; choice of the corners among young adults (i.e., University students) when they were in the VR setup was compared to that when they were in a real environment. Next, the same VR setup was used with different environment, namely a series of hallways, to investigate the difference between young and older adults during navigational task. During this experiment, young and older adults were compared in the use of spatial cues after learning a path from a start point to a goal within an environment. Specifically, the spatial cues were manipulated during testing phase to investigate the reliance onto the cues during the search of the goal among young and older adults. As the results were not conclusive, another comparison was made with a focus of learning a goal location in an environment. A serious game containing hexagonal rooms running on iPad was used to test young and older adults' ability to learn a location in the rooms.

The specific objectives of this study were to:

1. design a VR room, as a replica of a real room, for experiments using reorientation paradigm.
2. compare the choice of corner selection between the VR and real rooms among young adults (university students) to investigate how naturalistic an immersive VR setup is.
3. design another series of VR hallways for navigation experiment to investigate geometrical and featural cues' usage among young and older adults.
4. investigate the difference in reliance on featural cues among young and older adults, using a serious game in a 2D VR hexagonal room.
5. evaluate the feasibility of the above serious game as a training tool for older adults to enhance their independence of use of features for wayfinding.

1-6. Report Organization

This report is divided into five chapters including this introductory chapter, which describes background, related studies and the objectives of the thesis. The next four chapters are consisted of two published papers in peer-reviewed Journals (Chapter 2 and Chapter 3), one paper to be submitted (Chapter 4) followed by Chapter 5 summarizing the findings and suggested future work. Chapter 2 covers the objectives #1 and #2 to assess the feasibility of an immersive VR setup for human spatial cognition study. Chapter 2 concludes the use of the immersive VR is feasible for human spatial cognition study with a certain limitation; particularly when geometry and feature are presented in a conflict manner, during which the participants had to choose either, the participants relied more to geometry in the real environment while they relied more to feature in the VR. Otherwise, the use of the spatial cues between the real and VR environments were mostly comparable, providing similar spatial perception. The findings allowed the research to move forward to Chapter 3, which covers the objective #3, comparing young and older adults in their usage of geometry and feature during their navigation in immersive VR environments (hallways). The results provided an insight of difference between the young and older adults. However, the study revealed the immersive VR caused cyber sickness, which is one of the limitations of such a VR setup. Overall, the findings discussed in Chapter 2 and Chapter 3 suggest the featural cues were heavily used than the geometrical cues in VR domain. To investigate whether finding a target without heavily depending on featural cues is possible, Chapter 4, which contains the objectives #4 and #5, addresses the feasibility of a serious game framework to train usage of geometrical cues more than the featural cues in a 2D non-immersive VR setup.

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Chapter II. Evaluation of an Immersive Virtual Reality for Spatial Cognition Study

Navigation ability is a crucial skill of our daily life; however, the mechanism involved in navigation is not yet clear. Reorientation paradigm, during which investigates the process of recovering orientation, demonstrates flexibility of humans' usage of geometrical and featural cues. The usage of the cues is sensitive to the design of the environments; for example, the environment's size and platforms presenting an environment (i.e., real versus virtual) may change the reliance of the type of cues to reorient. Recent technology advances permit lightweight and portable virtual reality (VR) headsets that immerse humans better than a VR setup using a computer monitor screen; thus, claiming to provide better replacement for experiments run in real physical environments. However, can we use the cutting-edge immersive VR setup as a replacement of real environment for human spatial cognition study? To address this research question, humans' reorientation performance between an immersive VR environment to a real environment is compared using the reorientation paradigm to evaluate the spatial perception provided in the immersive VR setup.

Orientation in Virtual Reality Does Not Fully Measure Up to the Real-World

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Abstract

Adult participants learned to reorient to a specific corner inside either a real or virtual rectangular room containing a distinct featural object in each corner. Participants in the virtual-reality (VR) condition experienced an immersive virtual version of the physical room using a head-mounted display (HMD) and customized manual wheelchair to provide self-movement. Following a disorientation procedure, people could reorient by using either the geometry of the room and/or the distinct features in the corners. Test trials in which the different spatial cues were manipulated revealed participants encoded features and geometry in both the real and VR rooms. However, participants in the VR room showed less facility with using geometry. Our results suggest caution must be taken when interpreting the nuances of spatial cue use in virtual environments. Reduced reliability of geometric cues in VR environments may result in greater reliance on feature cues than would normally be expected under similar real-world conditions.

Introduction

Successful navigation requires encoding and recall of spatial cues from one's environment. Visual-based spatial cues can be broadly categorized as either *geometric* (e.g., distance or direction) or *featural* (e.g., color or pattern). Both geometric and featural cues can be used to form a long-lasting cognitive map as first theorized by O'Keefe and Nadel in 1978 [1].

Studying how humans navigate in the real world presents researchers with a host of practical problems that can be difficult to overcome. Fortunately, advances in computer technology have enabled researchers to use realistic computer-generated virtual reality (VR) environments to simulate the real world, which provide them with some key advantages. Firstly, VR environments allow for a greater degree of control over variables of interest than real environments can typically offer [2]. Secondly, they can more easily be used in conjunction with neuroimaging techniques to study brain regions involved while a person is actively engaged in a VR navigation task [3,4]. Finally, when examining spatial memory in vulnerable populations who are physically and/or cognitively compromised [5], VR environments offer a less stressful and physically demanding experience.

However, the advantages of using VR technology to study spatial cognition are only relevant if the processes involved in virtual navigation are similar enough to those used in real navigation that accurate inferences about spatial behavior can be drawn. Research has largely supported the effectiveness of VR in recreating the actual spatial experience, even when the VR environment is relatively non-immersive, as is the case when it is presented on a desktop display [6-11]. With the increasing availability and decreasing price point of head-mounted displays (HMD), immersive VR technology allows for physical sensations such as head movement and, when paired with external devices, locomotion. HMDs are portable and lightweight, and allow participants to obtain a greater sense of presence than desktop simulations can typically provide [12,13]. Overall, the use of VR as a practical method for studying spatial cognition has yielded reliable experimental results and will undoubtedly continue for the foreseeable future, especially given the continual refinement and growing accessibility of VR systems. But although many studies have used VR to examine broad questions relating to spatial cognition, few studies have specifically examined whether the nuances of how spatial cues are used in VR and real-world environments are similar.

The goal of our study was to investigate whether geometric and featural cue reliance differs between VR and real-world environments. To examine this question we employed a robust reorientation paradigm, originally used by Cheng (1986), to study spatial behavior in rats, but has since been used to study spatial behavior in a range of different animals, including humans [14-16]. The paradigm involves a rectangular room with distinct features located at each one of the corners. Typically, during a training phase, a participant learns that a reward is hidden in one of the corners (and reliably associated with one of the features), and so the participant learns to always search for the reward at that location at the exclusion of the other three corners. Using subsequent transformation tests, the spatial properties of the environment are manipulated, revealing the cues the participant was using during training (e.g., the geometric properties of the corner or the featural cue located at the corner). Using this paradigm, we were able to examine the degree to which participants use features and geometry in VR and real-world environments.

Methods

Participants

Undergraduate students (mean age = 21.7 years), with normal or corrected-to-normal vision, enrolled in the University of Manitoba's Introductory Psychology course participated. The VR and real-world conditions had 32 participants each (16 men and 16 women). All reported experimental protocols were approved by the Psychology/Sociology Research Ethics Board at the University of Manitoba (#HS11295). The methods were carried out in accordance with these relevant guidelines and regulations. Informed consent was obtained from all participants.

Apparatus and General Procedures: Real-World

The training and testing environment was a fully enclosed rectangular room (2.44 m wide, 4.88 m long, and 2.44 m tall) within a larger pre-existing room. The rectangular room was constructed from a wooden frame with opaque fabric curtains hung from floor to ceiling to form identical walls preventing any visual cues outside the structure from being visible. The carpeted floor was neutral-colored and contained no discernible marks or patterns. A sheet attached to the top served as a translucent ceiling and allowed the room to be uniformly lit by diffuse lighting from overhead lights. A camera (GoPro Hero 3 + Silver) was attached to the middle of the ceiling and was used to record all trials. The features (a red cube, blue cylinder, yellow cone and green sphere) all approximately fit within a size of

0.5 m wide, 0.5 m long and 0.5 m tall to maintain a relative size constancy between comparable features used in the virtual environment.

Participants were trained and tested individually. Trials began with the experimenter disorienting participants by blindfolding them and walking them randomly around the room, occasionally turning them slowly in circles, before stopping at one of four pseudo-randomized start positions located at the center of each wall. The blindfold was then removed, and participants were instructed to “find the correct corner” by approaching and pointing to their choice corner. During training trials, participants were allowed as many choices as needed to find the correct corner and received feedback after each choice; during testing trials no feedback was provided and trials ended following a single choice.

Apparatus and General Procedures: VR Environment

The VR version of the real-world environment was measured in virtual units (vu) in which each vu corresponded to one meter in the real-world environment. The rectangular environment measured 3.30 vu wide × 6.87 vu long × 3.00 vu high (for a comparison of the real-world environment and virtual environment see Fig. II-1). Comparable features from the real-world environment (red cube, blue cylinder, yellow cone and green sphere) were computer-rendered and located at each corner. The game engine tracked and recorded the position and orientation of the VRNChair [17] as it moved through the VR environment.

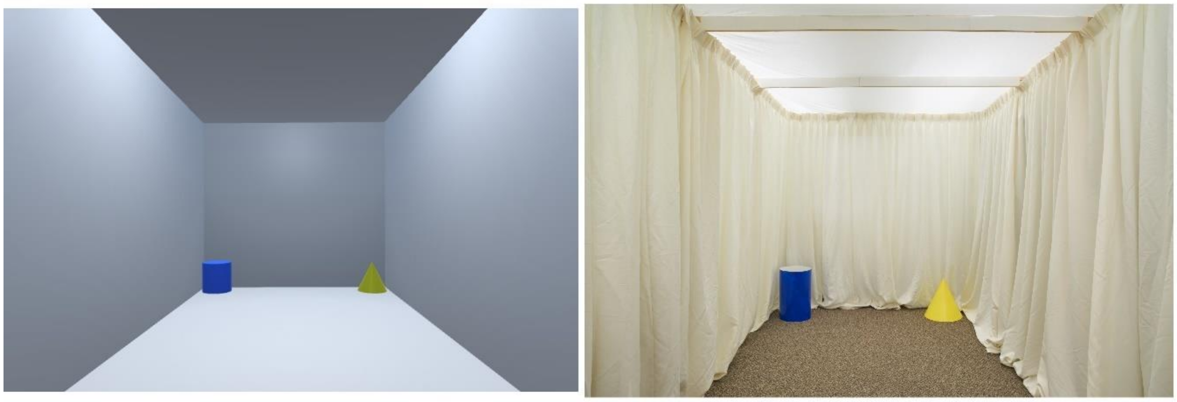

Figure II- 1. A comparison of the virtual room (left) and the real-world room (right).

Participants were trained and tested individually. Participants viewed the virtual environment through the HMD (Oculus Rift DK2) and moved within the environment using a specially designed VRNChair (Fig. II- 2). The participants were instructed to “find the correct corner” and made a choice by moving to a corner and pressing a button located at their fingertip. Since the VRNChair provided an unrestricted range of movement within the VR room, participants were free to look around and fully explore the environment before making a selection. Between trials participants removed the HMD to limit any discomfort or possible vertigo. Otherwise, training and testing procedures were identical to the real-world.

Figure II- 2. The VRNChair including laptop and HMD. The inset photo gives an example of the virtual room as viewed through the HMD. Physical movement of the VRNChair translated to movement within the virtual room. Choices were made by pressing a button attached to the participant's right finger (not shown).

Training Phase

The training phase for both the real-world and VR versions consisted of eight trials. Each participant was randomly assigned a "correct" corner, counterbalanced across participants, which was defined both by its geometry (e.g., short wall to the right of a long wall), and by the distinct feature cue located at the corner (e.g., blue cylinder; Fig. II- 3a). Participants were required to locate their correct corner with their first choice on the last two trials to pass training, and subsequently begin testing; participants who failed were replaced with another participant of the same sex. A total of 5 participants failed to pass training in the real-world condition and no participants failed training in the VR condition.

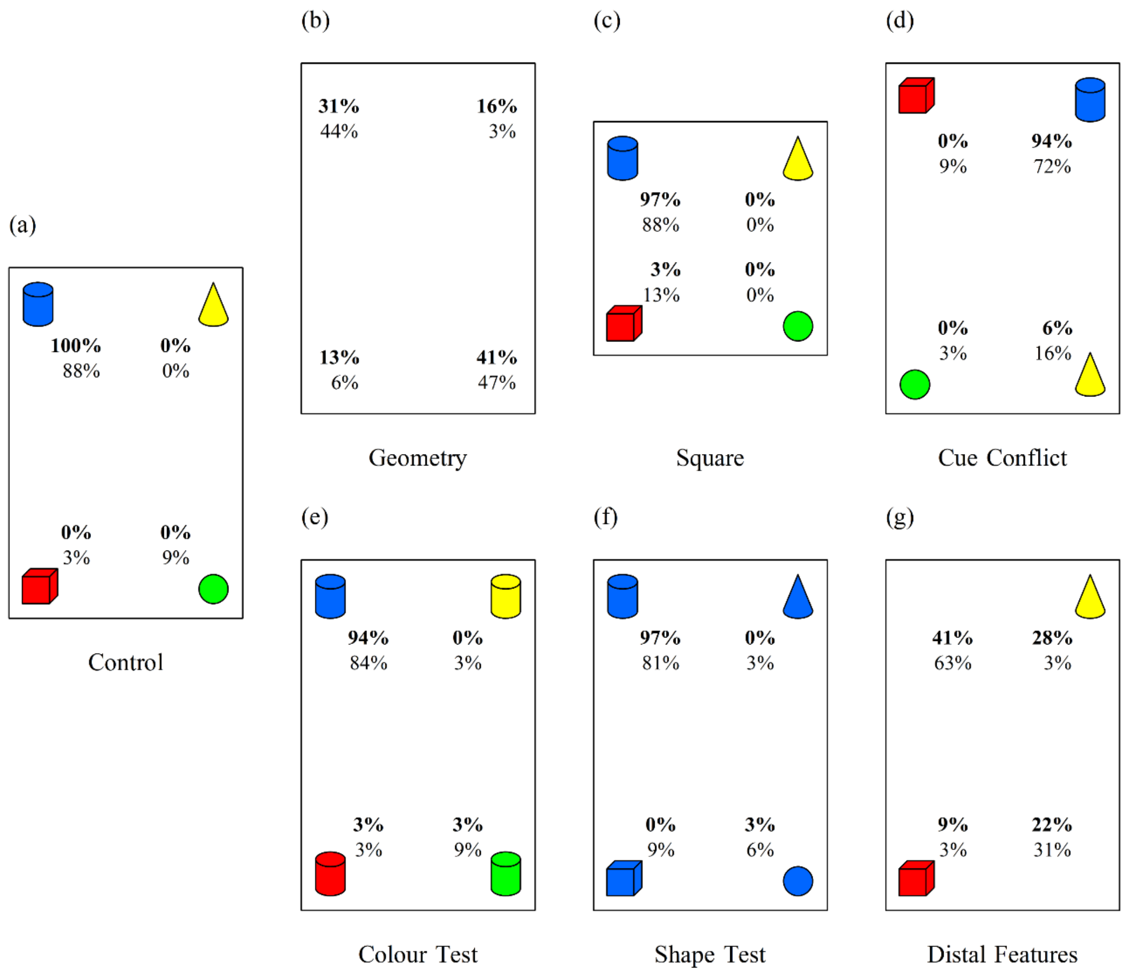

Figure II- 3. Schematic representations of the room during training/control and all testing conditions. For illustrative purposes only, the top left (i.e., the corner containing the blue cylinder) has been assigned as correct, but during the experiment this was counterbalanced across participants. Numbers represent the percentage of choices to each corner in the virtual environment and real-world environment for each testing condition (percentages for the virtual environment are indicated in bold). Note this figure is not drawn to scale.

Testing Phase

Six randomized testing trials, presenting a modified environment, were administered (see below). The testing phase always concluded with a training trial and a control trial (identical to the training trial except limited to a single choice and no feedback was provided). The purpose of these trials was to evaluate whether participants continued to select their correct corner after experiencing the testing phase.

Geometry Test. During this test, all of the features were removed from the corners, resulting in an environment void of all distinctive feature information (Fig. II- 3b). This test assessed whether participants incidentally encoded the geometric properties of the environment during training, despite the presence of a unique and salient feature in each of the corners (which were 100% reliable). Had the participants encoded geometry we would expect them to limit their choices to the two geometrically correct corners (the correct corner and its rotational equivalent), whereas if they had not encoded geometry we would expect an equal distribution of choices among the four corners.

Square Test. During this test, the features were organized in the same arrangement relative to training, but the environment itself was square in shape - all walls were equal in length thus removing any informative geometric information (Fig. II- 3c). This test examined whether participants could use the feature cues when all informative geometric cues had been removed, by limiting their choices to the one featurally correct corner.

Cue Conflict Test. During this test, the four features from training were present, but each feature was relocated one corner clockwise from its position during training (Fig. II- 3d). This test deliberately placed geometric and featural information in conflict by placing the correct feature in a geometrically incorrect corner. Therefore, this test required participants make a choice based on either geometric (choosing between the two geometrically correct corners) or featural information (choosing the corner which contained the correct feature), which allowed us to examine participants' preference, or weighing, of these cues.

Colour Test. During this test, all four features retained their same colour property as during training, but the shape property was modified such that they were all the same shape as the feature in the participant's correct corner from training (Fig. II- 3e). For example, if the feature in the correct corner had been a blue cylinder, all the other features during this test would be shaped as a cylinder (i.e., a yellow cylinder, red cylinder, blue cylinder, and green cylinder). This test examined whether participants had encoded the colour of their correct feature during training, independent of its shape.

Shape Test. During this test, all four features retained their same shape property as during training, but the colour property was modified such that they were all the same colour as the feature in the participant's correct corner during training (Fig. II- 3f). For example, if the feature in the correct corner had been the blue cylinder, all the other features during this test would be blue (i.e., a blue cone, blue cube, blue cylinder, and blue sphere). This test examined whether participants had encoded the shape of their correct feature during training, independent of colour.

Distal Features Test. During this test, the feature in both the correct corner and the diagonally opposite corner were removed (Fig. II- 3g), leaving only the two features in the geometrically incorrect corners. This condition examined whether participants were able to use features in the distal corners to determine the position where the correct corner should be located.

Statistical Analyses

Each testing condition contained either a correct response whereby a person received a score of 1 or an incorrect response whereby a person received a score of 0; the criteria for determining what defined a correct response differed for each testing condition. Binomial tests were used to examine the percentage of choices made to the correct corner(s) for each testing condition separately for the real-world and virtual environments. Independent proportions z-tests were then used to compare the percentage of correct responses between the real-world and virtual environments for each testing condition.

As both the Geometry and Distal Features tests allowed for a strategy whereby a choice was considered correct if it was made to either of the geometrically correct corners (i.e., the correct corner or its diagonal opposite, herein referred to as the rotational corner), additional Wilcoxon signed-rank tests examined whether choices differed between these two corners.

Data Availability

All data generated or analyzed during this study are included in this published article (and its Supplementary Information files).

Results

Control Test

The purpose of the Control Test was to confirm participants retained knowledge of their correct corner throughout the testing phase. During this test, all features were located in the corners as during training, with the only difference being no visual or verbal feedback was provided after the participant made a choice. A choice to the correct corner was considered correct and a choice to any other corner was considered incorrect.

Binomial tests showed the percentage of choices to the correct corner significantly exceeded choices to all other corners in both the real-world (91% vs. 9%, respectively; $p < 0.001$) and VR environment (100% vs. 0%, respectively; $p < 0.001$). A comparison of correct choices did not differ between the real-world and VR environments ($Z = 1.77$, $p = 0.08$).

Overall, results from the Control test show that participants in both environments retained a memory for their correct corner throughout the training phase and in the absence of feedback (Fig. II- 3a).

Geometry Test

The purpose of the Geometry test was to determine whether participants had incidentally encoded the geometric properties of the room during training. During this test, all features were removed from the corners and only the geometric cues from the properties of the environment itself were informative. Since the correct corner and the rotational corner were geometrically identical, a choice to either of these corners was considered a correct choice and a choice to either of the two remaining corners was considered an incorrect choice.

Binomial tests showed the percentage of choices to the correct geometric corners significantly exceeded choices to the incorrect geometric corners in both the real-world (91% vs. 9%, respectively; $p < 0.001$) and VR environment (72% vs. 28%, respectively; $p = 0.02$). Additional Wilcoxon signed-rank tests showed choices to the positive and rotational corners did not differ in either the real-world ($Z = 0.186$, $p = 0.853$) or the VR environments ($Z = 0.626$, $p = 0.532$), indicating participants were unable to distinguish between these two geometrically identical corners (this is strong evidence the participants were not using any uncontrolled cues, such as hallway noise in the real-world room). A comparison of geometrically correct choices between the real-world and VR environments was marginally significant ($Z = 1.92$, $p = 0.052$).

Together these results show that geometry was encoded incidentally in both environments as participants were able to accurately use the geometric properties in both the real-world and VR settings, although geometric encoding was more pronounced in the real-world (Fig. II- 3b).

Square Test

The goal of the Square Test was to determine whether participants had encoded the feature in their correct corner, and could use this cue independent of geometry. During this test any informative geometric cues were removed leaving the four distinctive features from training. A correct choice was one made to the corner containing the correct feature and an incorrect choice was one made to any of the other three corners.

Binomial tests showed the percentage of choices to the corner containing the correct feature significantly exceeded choices to all other corners in both the real-world (88% vs. 12%, respectively; $p < 0.001$) and VR environments (97% vs. 3%, respectively; $p < 0.001$). A comparison of choices to the correct feature between the real-world and VR environments was not significant ($Z = -1.4$, $p = 0.16$).

Overall, results from the Square test showed participants could use their correct feature to reorient independent of informative geometry in both the real-world and VR environment (Fig. II- 3c).

Cue Conflict Test

The purpose of the Cue Conflict test was to determine whether participants relied more on either featural or geometric cues when the two cue types provided conflicting information as to the location of the correct corner. During this test, each feature was repositioned one corner clockwise from its location during training, meaning if a participant made a correct featural choice they would do so by making an incorrect geometric choice (and vice-versa).

Binomial tests showed the percentage of choices to the correct feature significantly exceeded choices to the correct geometry in both the real-world (72% vs. 28%, respectively; $p = 0.02$) and VR environments (94% vs. 6%, respectively; $p < 0.001$). A comparison of featurally correct choices between the real-world and VR environments was significant ($Z = -2.32$, $p = 0.02$), indicating a stronger preference for choosing the correct location according to featural information in the VR environment compared to the real-world environment.

Overall, results from the Conflict test showed participants relied more heavily upon featural cues over geometric cues when these two sources provided conflicting information as to the goal location. Furthermore, this weighing of featural cues was heavier for participants in the VR environment than for participants in the real-world environment (Fig. II- 3d).

Colour Test

The purpose of the Colour test was to determine whether participants had encoded the colour of their correct feature. During this test, the colour of each feature was different (and consistent with training) but all were the same shape as the correct feature. A choice was considered correct if it was made to the corner containing the feature with the same colour as the correct feature during training; a choice was incorrect if it was made to any of the other three corners.

Binomial tests showed the percentage of choices to the corner containing the correct-coloured feature significantly exceeded choices to all other corners in both the real-world (84% vs. 16%, respectively; $p < 0.001$) and VR environments (94% vs. 6%, respectively; $p < 0.001$). A comparison of correct choices between the real-world and VR environments was not significant ($Z = -1.2$, $p = 0.23$).

Overall the results show participants had encoded the shape of their correct feature independent of the colour in both the VR and real-world environments (Fig. II- 3e).

Shape Test

The purpose of the Shape test was to determine whether participants had encoded the shape of their correct feature. During this test, the shape of each feature was different (and consistent with training) but all were the same colour as the correct feature. A choice was considered correct if it was made to the corner containing the feature with the correct shape as during training; a choice was incorrect if it was made to any other corner.

Binomial tests showed the percentage of choices to the corner containing the correct-shaped feature significantly exceeded choices to all other corners in both the real-world (81% vs. 19%, respectively; $p = 0.001$) and VR environments (97% vs. 3%, respectively; $p < 0.001$). However, unlike the Colour test, a comparison of correct choices between the real-world and VR environments was significant ($Z = -2.0$, $p = 0.046$), indicating a more accurate encoding of the correct feature's shape in the VR environment compared to the real-world environment.

Overall the results show participants had encoded the shape of their correct feature when they were learning the task, and this encoding was more accurate in the VR environment than it was in the real-world environment (Fig. II- 3f).

Distal Features Test

The goal of the Distal Features test was to determine whether participants had encoded the features located in the two geometrically incorrect corners (the distal corners), or whether the participants had only encoded those feature(s) in the geometrically correct corners. During this test the features in the correct corner and rotational corner were removed (geometrically correct corners) leaving only the features in the two geometrically incorrect corners; the feature in the rotational corner was removed to eliminate the possibility that participants could determine their correct corner as the only one without a feature.

Binomial tests showed the combined percentage of choices to the geometrically correct corners was significantly greater than choices to the geometrically incorrect corners in the real-world environment (94% vs. 6%, respectively; $p < 0.001$) but not in the VR environment (63% vs. 37%, respectively; $p = 0.215$). A comparison of combined choices to these corners between the real-world (94%) and VR environments (63%) was significant ($Z = 3.02$, $p = 0.003$), showing participants in the real-world room chose these geometrically correct corners more than participants in the VR room; indeed participants' choices in the VR room were not significantly different from chance (50%; $t = 1.44$, $p = 0.161$; one-sample t-test).

Wilcoxon signed-rank tests comparing choices between the correct and rotational corners were not significant in either the real-world (63% vs. 31%, respectively; $Z = 1.83$, $p = 0.068$) or VR environment (41% vs. 22%, respectively; $Z = 1.34$, $p = 0.18$), establishing that participants were not able to choose the location of their correct corner more than the rotational corner in either environment type.

Overall, results show participants did not encode the relative position of the distal features in either type of environment. However, when only the distal features were available the participants in the real-world resorted to using the geometric cues, whereas the participants in the VR environment did not choose the geometrically correct corners more often than chance (Fig. II- 3g).

Discussion

Overall, our results support two main conclusions. Firstly, they support the general use of VR for studying spatial navigation, although caution must be taken when interpreting how participants are encoding spatial cues. Participants were easily able to navigate the VR room, using the HMD for visual input and the customized wheelchair (VRNChair) to provide movement, and the spatial decisions they made were *generally* comparable to those in the real-world room. However, clearly the use of spatial cues differed in *degree* - geometric encoding was not as accurate in the VR environment as in the real-world environment, leading to our second main point. Although the geometry and feature properties were encoded by participants in both environments, the geometric cues were relied upon more heavily in the real environment than in the VR environment. Thus, geometry in virtual settings appears not to be encoded by participants in a manner analogous to the real-world, even in our highly immersive VR procedure. This is an important finding for all studies of orientation and navigation using a VR approach.

Encoding Features

The main test to determine whether people had encoded feature cues independent of the room geometry was the Square test. During this test, all walls of the room (either VR or real-world) were of equal length which removed any informative geometric information, but the four features from training were still present. Not surprisingly, in both the VR and real-world rooms, participants chose the corner containing their correct feature, thus establishing they were able to use their correct feature in environments without informative geometric information. During the Cue Conflict test, which was conducted in a rectangular-shaped room, each feature was repositioned to the nearest corner clockwise to where it had been during training, a condition that placed featural and geometric information in conflict. In both the VR and real environments, participants chose the corner that contained their correct feature even though it was now in a geometrically incorrect corner, thus showing primary weighing of features in both environments.

To determine whether people had encoded the colour and shape of their correct feature independently, two additional tests were conducted whereby these two properties were dissociated. The Colour test showed people could identify the correct corner using only colour information and the Shape test showed they could identify the correct corner using only shape information; this finding was consistent in both the VR and real-world conditions. However, one unexpected finding was participants in the VR environment were more accurate at using shape information from the features compared to those in the real environment. At present we are not sure why shape information per se may have been more salient for people in the VR condition. However it should be noted that shape recognition was high in both environments (97% in VR and 81% in real-world) and these differences were only moderately different from those of colour encoding (94% in VR and 84% in real-world).

The tests described thus far support that people in both the VR and real-world environments clearly encoded their correct feature during training procedures. But did they also encode the features located in the other distal (geometrically incorrect) corners? This question was examined during the Distal Features test in which only the features located in the two geometrically *incorrect* corners were present during test trials. Had people sufficiently encoded either (or both) of these features, they could have used this information to identify their correct corner, allowing them to limit their choices to only this correct corner and avoid choosing the rotationally equivalent corner. This did not happen, either in the VR or the real environment, suggesting people relied upon the feature located in their correct corner, and failed to encode the relative location of the other features.

Encoding Geometry

During the Geometry test, all the features present during training were removed, leaving only wall length and left-right sense to guide people to their correct corner. Results from the Geometry test in both the VR and real-world rooms showed people could use geometry to focus their choices to the geometrically correct corners (72% in VR and 91% in real-world). The conclusion therefore is people in both the VR and real-world rooms encoded the geometry of the space itself. But was the accuracy of this encoding equivalent in both environments? When comparing correct geometric choices between VR and real-world environments there was a marginally significant ($p = 0.052$) advantage favoring more accurate encoding of geometry in the real-world compared to the VR environment. This finding suggests environmental geometry may have been a more salient (and consequently more useful) spatial cue in the real-world than it was in the VR room, an interpretation that is further supported by results from both the Cue Conflict and Distal Features test.

During the Cue Conflict test the features from training were present in each of the corners, except each feature was now relocated one corner clockwise from the corner it occupied during training. This arrangement required participants make a choice between either the correct geometry or the correct feature. In both the VR and real-world rooms participants chose the corner with the correct feature over the geometrically correct corners, but this preference was significantly stronger in the VR environment than in the real-world environment (94% vs. 72%), a finding that can reasonably be attributed to weakened influence of competing geometry in the VR room. Furthermore, during the Distal Features test, although overall the participants were unable to use distal features to choose their correct corner in either environment, those in the real-world room resorted to a geometric strategy, whereas participants in the VR room did not. This result again supports geometric information was more salient in the real-world environment compared to the VR environment.

The findings of reduced sensitivity or saliency of geometry in the VR room is consistent with similar research showing that distance perception is generally underestimated in VR environments compared to real environments [18-20]. A possible explanation for this underestimation is the field of view provided by the HMD (approximately 100 degrees) is narrower than our natural visual field. However, previous experiments have shown that specifically reducing observers' field of view does not have a direct effect on distance perception in either real-world [21] or virtually-rendered environments [22].

A second possibility is binocular depth perception may have been compromised for people who experienced the VR condition. Binocular depth perception results from the slight displacement of the visual field between the left and right eye [23], a condition that is simulated inside the HMD through the calibration of inter-pupil distance for each person.

However, since this calibration depends on the subjective responses of the person as he/she views images only in VR, perfect calibration is often difficult to achieve since slight errors typically go unnoticed by the user [24]. Therefore, the binocular depth cues provided by HMDs in general can best be described as a close approximation of the real-world experience, with any differences being expressed in the imperfect perception of geometric properties.

Conclusion

During this study we found that reorientation strategies in VR and real-world environments were qualitatively equivalent. People encoded the featural and geometric cues, and when required to make a choice between these two cue types they chose features, regardless of whether it was in a VR or real-world setting. But upon closer inspection, the use of these spatial cues also differed in *degree* in that geometric encoding was not as accurate in the VR environment as in the real-world environment. Given that much of the current reorientation and navigation research is conducted using virtually rendered environments [25-28], our findings provide an important level of insight (as well as a point of caution) for researchers when interpreting results from VR settings. The metric properties of virtual environments appear not to be encoded by participants in a manner analogous to encoding in real-world environments, even in a highly immersive VR environment as was used in our current study. For VR applications designed to meet the needs of a more general public (e.g., gaming or information displays) this discrepancy is not likely to pose a problem, but for the more stringent standards required of spatial cognition research this is an issue which needs to be acknowledged and addressed.

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Chapter III. Comparing Young and Older Adults' Navigational Abilities Using an Immersive Virtual Reality

In the previous chapter, an immersive VR setup was evaluated for human spatial cognition studies in terms of the usage of geometrical and featural cues using the reorientation paradigm. To sum, the geometrical cue is less salient in the immersive VR than that in a real environment yet geometrical cue itself was perceived in the immersive VR setup. While the reorientation paradigm reveals the usage of the spatial cues in room-scale environments, investigation of such usage in a large-scale environment during a way-finding task has not been conducted, perhaps due to the difficulty of geometry manipulation in a real environment. Aside from the spatial cues' usage, aging decline in navigation has been reported in route-learning and use of allocentric reference frame. Generally speaking, older adults tend to be less efficient during navigational tasks than their younger counterparts. Thus, it is of our interest whether the use of spatial cues during the route-learning task in a large environment (i.e., larger than a room) differs between young and older adults. In this chapter, environments of grids of hallway were designed using the VR setup described in the previous chapter, and the geometrical and featural cues usage was compared between the two age groups.

Older adults show less flexible spatial cue use when navigating in a virtual reality environment compared to younger adults

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Abstract

Daily life requires accurate navigation, thus better understanding of aging on navigational abilities is critical. Importantly, the use of spatial properties by older and younger adults remains unclear. During the current study, younger and older human adults were presented with a virtual environment in which they had to navigate a series of hallways. The hallways provided two general types of spatial information: geometric, which included distance and directional turns along a learned route, and featural, which included landmarks situated along the route. To investigate how participants used these different cue types, geometric and/or landmark information was manipulated during testing trials. Data from 40 younger (20 females) and 40 older (20 females) adults were analyzed. Our findings suggest: 1) both younger and older adults relied mostly on landmarks to find their way, and 2) younger adults were better able to adapt to spatial changes to the environment compared to older adults.

Keywords: spatial cognition, geometry, landmarks, aging, navigation, virtual reality

Introduction

Navigation requires that one first establish an accurate sense of heading. During visually-guided orientation, research has shown that navigators encode both geometric and featural cues [1]. The former includes direction and distance information (e.g., the length of a wall), whereas the latter includes non-metric information (e.g., the specific color pattern of a wall). Featural cues also include specific aspects of landmarks, whether they are proximal to a location or more distal. Landmarks that are close to a location can act as a beacon for that location in which case spatial learning is quite simple; landmarks that are more distal pose a more complex challenge in that their spatial arrangement relative to a location must be remembered in order to be effective. Although much research has been conducted into how these cues are used to navigate, less is known about how the use of these cues change with advanced age.

To investigate how both geometric and featural properties can be used by a subject to find their way within a space, a reorientation paradigm is commonly employed since it can easily segregate these two cue types using a simple environment [2-5]. During reorientation studies, a subject learns to locate a hidden target in one corner of a walled space when both geometric and featural cues are available during a learning phase, and again searches for the hidden target after the cues are manipulated or removed during a testing phase [5]. Where subjects choose to search during these test trials can reveal which spatial cues they relied upon most when initially learning about the environment. During test trials, in which geometry and features provide conflicting information, participants have to choose which type of cue they find more reliable [3]. Results from these studies show that people readily encode both geometric and featural cues [2, 4, 5], with greater reliance on geometry in smaller environments and features in larger environments [3]. However, since the participants in many of these studies have been either young children or otherwise healthy younger adults [6], comparatively less is known about the effect that advanced age has on such encoding.

Previous research has shown that advanced age can affect navigational ability in different ways [7-11]. For example, when spatial knowledge was examined by measuring the duration and distance traveled during a complex-maze route-learning task, results showed more deviations from the correct route by older (65+ years) adults compared to younger adults (< 45 years) [8]. Similar findings were reported using a computerized version of the *Morris Water Maze* task whereby older participants (mean age 73.7 years) spent less total time, and devoted a smaller proportion of the path length traveled, inside the correct quadrant, compared to younger adults (mean age 28.6 years) [9]. In another study [10], younger (mean age 21.8 years) participants were more able to employ a novel short cut through a VR city environment than older (mean age 68.7 years) participants. It should be noted that the use of a novel shortcut is considered to be the hallmark measure of a complex mental allocentric map complete with landmarks [11]. Generally speaking, older adults tend to be less efficient during navigation tasks than their younger counterparts; a difference that can often be traced to older adults being less effective at integrating distal landmarks into a stable spatial framework when learning new environments [7, 12-22].

Studies of spatial cognition have used both real environments [2, 3, 14-16] as well as virtual reality (VR) environments [4, 5, 7-10, 12, 13, 17, 19, 21, 22], with VR paradigms having the advantage of easily tracking and recording responses such as trajectories taken during trials and time to complete trials. A general assumption of VR paradigms is that spatial decision-making in a virtual world is largely transferrable to the real world [23-25], and their main strength is that they allow researchers to manipulate key elements of the environment such as altering room dimensions, changing start location of trials, or removing/relocating landmarks. More immersive VR designs, such as those using head-mounted displays (HMD) to display the environment to participants, have the added advantage of providing a more realistic navigational experience. The drawback of these designs, however, is that they can be prone to inducing motion-related fatigue which can affect stress levels and ultimately decision-making [26-29]. Research has generally shown that spatial cognition performance using these kinds of fully immersive paradigms do not differ substantially from paradigms employing more traditional desktop or laptop computer displays [29-31].

For the present study, we employed a paradigm that allowed participants to navigate within a VR environment (hallway complex) displayed to them via an HMD with movement provided by a custom designed wheelchair, called a VRNChair, which provided both proprioceptive and vestibular inputs to participants [32]. For those participants who experienced motion-related fatigue during initial training with the HMD, a switch from the HMD to a comparable laptop display was made, which provided us an opportunity to compare performance using both types of displays. Our specific goal was to examine whether the encoding of geometry and features differs between younger (mean age 26.2 years) and older participants (mean age 67.6 years). Specifically, when an environment is manipulated (i.e., by changing the geometry or removing some or all of the landmarks), do younger and older adults use different strategies when searching for a desired destination?

Method

Participants

A total of 51 older adults (28 females; mean age 67.6 ± 9.1 years) and 50 younger adults (28 females; mean age 26.2 ± 4.4 years) participated in this study; of that total, 21 participants either reported motion-related fatigue or failed to meet training criteria (see *Procedure* below), resulting in data from 80 participants being used in the final analyses. Older adults were recruited from a known participant pool of older healthy adults who had previously participated in an earlier unrelated virtual reality study [33]. Prior to the start of the experiment, cognitive abilities were tested using the Montreal Cognitive Assessment (MoCA) [34], which confirmed that all older participants met the standard for normal cognitive functioning. All younger adults were student volunteers recruited from the campus of the University of Manitoba. All participants signed a consent form approved by the Biomedical Research Ethics Board of University of Manitoba.

Virtual Reality Components and Materials

To investigate how participants navigated during the task, we designed a virtual hallway environment using Blender 2.74, which participants could view on either an Oculus DK2 head-mounted display (HMD) or a laptop display (see *Procedure* below). In order to move within the environment a custom-designed wheelchair, called the VRNChair [31], allowed the translation of real-world movement via the wheelchair to virtual movement within the VR environment.

The hallways each measured 27 × 32 × 2.44 virtual units (width × length × height) wherein 1 virtual unit (vu) corresponded to approximately 1 meter in real-world. We used Unity 5.1.3f [35] to design a custom game engine that integrated the hallway models, VRNChair, the HMD (Oculus Rift DK2) and logging system to record each participant's motion during trials. The HMD resolution was 1920 × 1080 with a total field of view of 106 degrees. As there were some participants who experienced discomfort while wearing the HMD, for these individuals we replaced the HMD with a 17-inch laptop display (resolution 1920 × 1080) while preserving the same field of view as the HMD. The experimental computer was equipped with a NVIDIA Geforce GTX 980m graphic card to draw the virtual environment on either the HMD or the monitor in a real-time without dropping frames.

Virtual Environment

The environment contained five hallways organized as grids running east-west (E-W) and north-south (N-S) with each hallway 2 vu wide. The area surrounded by each hallway is referred as one 'block', with each block measuring 3 vu in an E-W direction and 4 vu in a N-S direction, as depicted in a top-down view in Figure III- 1. The north and south side of the walls (except for the boundary of the environment) contained an identical orange door in the middle, each measuring 0.91 × 2.44 vu (width × height).

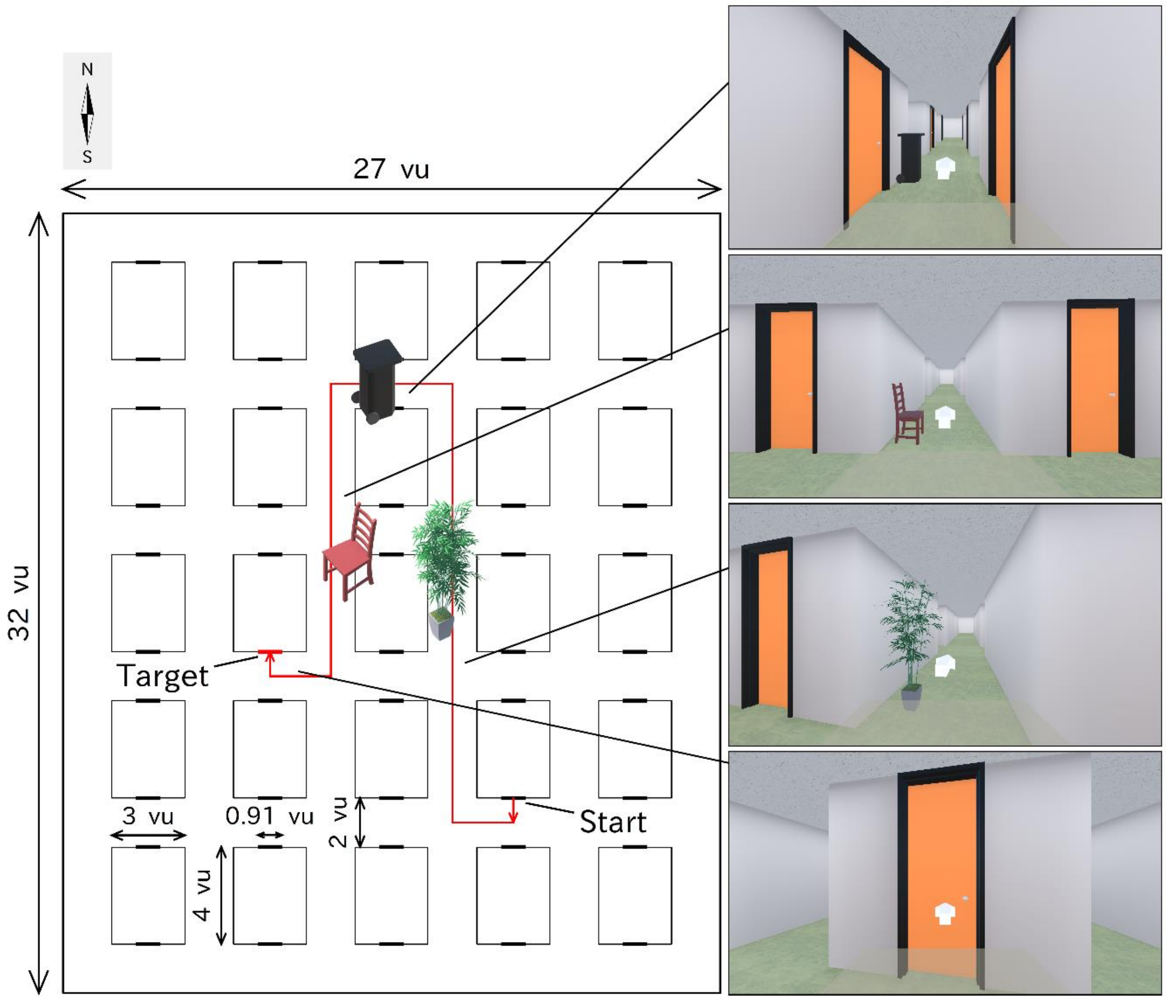

Figure III- 1. Left panel: A schematic top-down view of the training environment. The red line represents the predetermined route for all training trials. Along the route, there were 3 landmarks in the following order: a tree, a garbage bin, and a chair. Right panel: Screenshots of the virtual environment from several viewpoints. The white arrow in the middle of the screen guided the participants toward the target door.

Procedure

The HMD was calibrated for each participant by measuring their inter-pupillary distance using a tool provided by the manufacture (i.e., Oculus VR, LLC.). Next, the researcher instructed the participant to “find the correct door” in the virtual environment. To choose a door, the participant had to move close enough to it and click a button attached to their index finger. During training trials, participants could follow an onscreen arrow that would lead them toward the correct door.

The experiment proceeded in a set order for all participants (see Figure III- 2): First, two training trials were followed by one control trial, then two additional training trials followed by a second control trial, followed by a block of four testing trials (counterbalanced across participants), followed by a third control trial, and finally a Landmark Recognition trial. During the first trial, all participants used the HMD; for those participants who reported motion-induced fatigue prior to completion of the first control trial (the third trial in total), the HMD was replaced with a laptop display placed in front of them on the VRNChair and they were allowed to continue the experiment (see Figure III- 3 for a picture of both the HMD and laptop viewing conditions). For those participants who continued to report discomfort or dizziness following the fourth trial, the experiment was terminated and the data was not used. To limit the possibility of motion-related fatigue with the HMD, participants removed the HMD between trials. Altogether, the experiment took up to 60 minutes to complete.

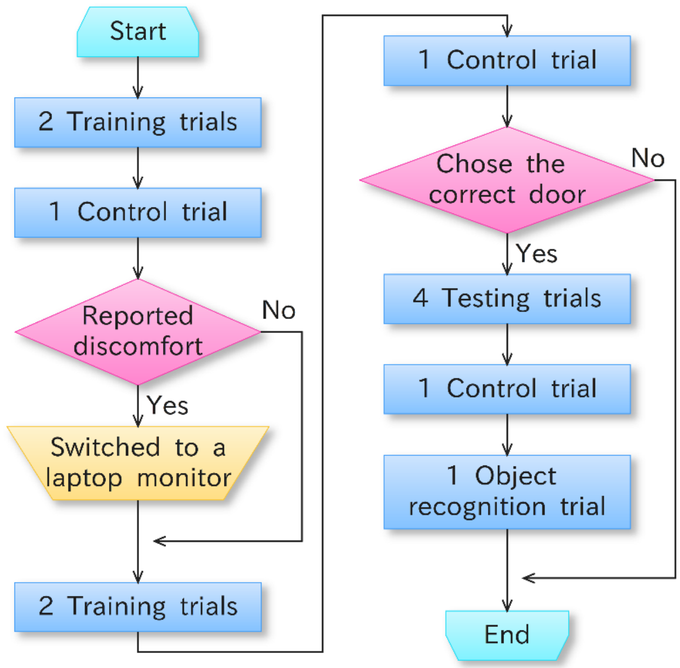

Figure III- 2. Methodological flowchart of the experiment.

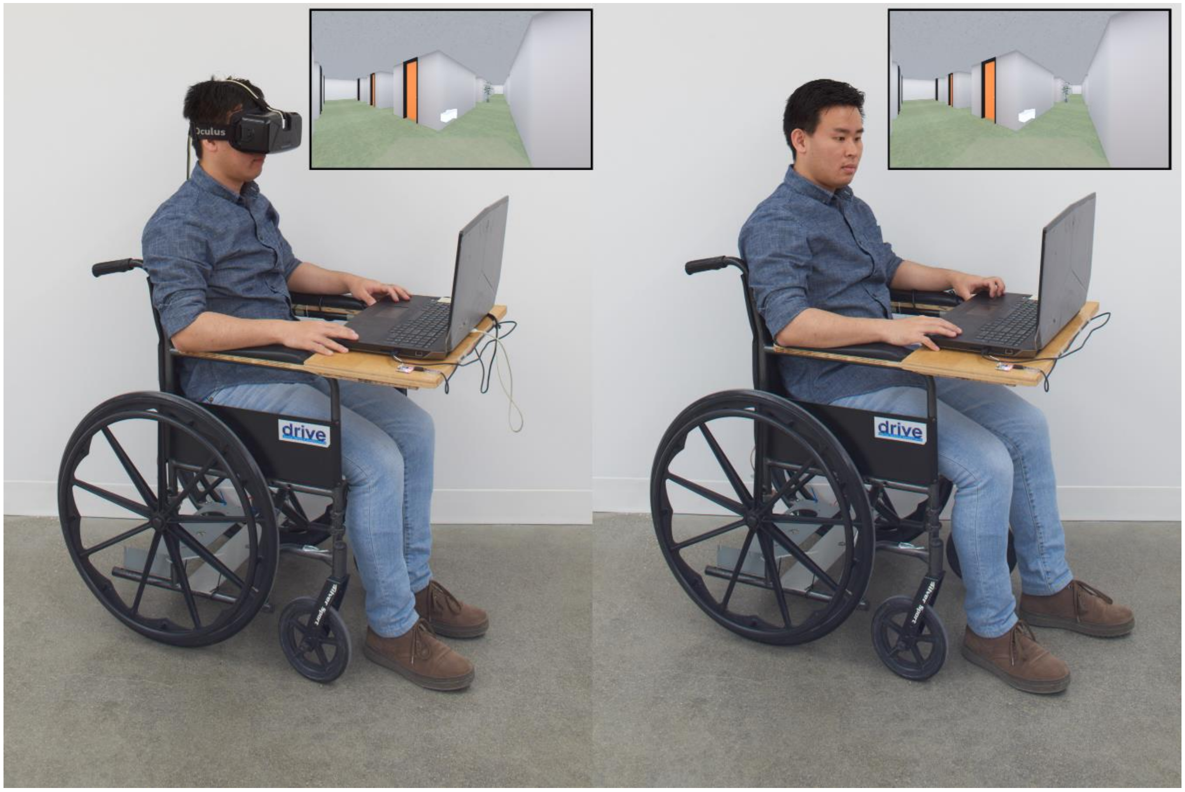

Figure III- 3. Two experimental setups: using a head-mounted display (left) and a laptop screen (right). The insets depict an example of the virtual environment that the participants observed.

Training and Control Trials

Participants started each trial from a consistent start location. Participants began with a learning phase consisting of training trials in which they could navigate the environment and learn the location of the correct door. During training trials, a white arrow guided the participant towards a target door along a predetermined route. Along the route the participant passed three landmarks in the same order: a plant, a garbage bin and a chair. When the participant missed one of the turns to follow the route, or made an incorrect turn, the onscreen arrow pointed them back onto the route. When the participant chose the correct door, the computer provided positive feedback with a verbal “good job” message and the trial ended.

Once participants had experienced two training trials they were presented with a control trial; this block of two training/one control trial was repeated twice (for a total of 6 trials). During control trials the environment was identical to that during training trials, except the white arrow was no longer visible and no verbal feedback was provided following a choice. Participants who chose the correct door at the end of the second control trial advanced to testing; if the participant chose an incorrect door the experiment was terminated.

Testing Trials

Each testing trial contained a different manipulation that allowed us to investigate the spatial properties that participants had encoded during training. Specifically, we examined whether the participants used the geometric properties of the route (i.e., distance and direction) or relied more on the landmarks.

No Landmarks. All three landmarks that were present during training (plant, garbage bin, and chair) were removed from the environment, while keeping the start location and metric qualities of the route intact (see Figure III- 4a). The purpose of this test was to investigate if the participants could locate the correct door without the landmarks present (i.e., using only metric information).

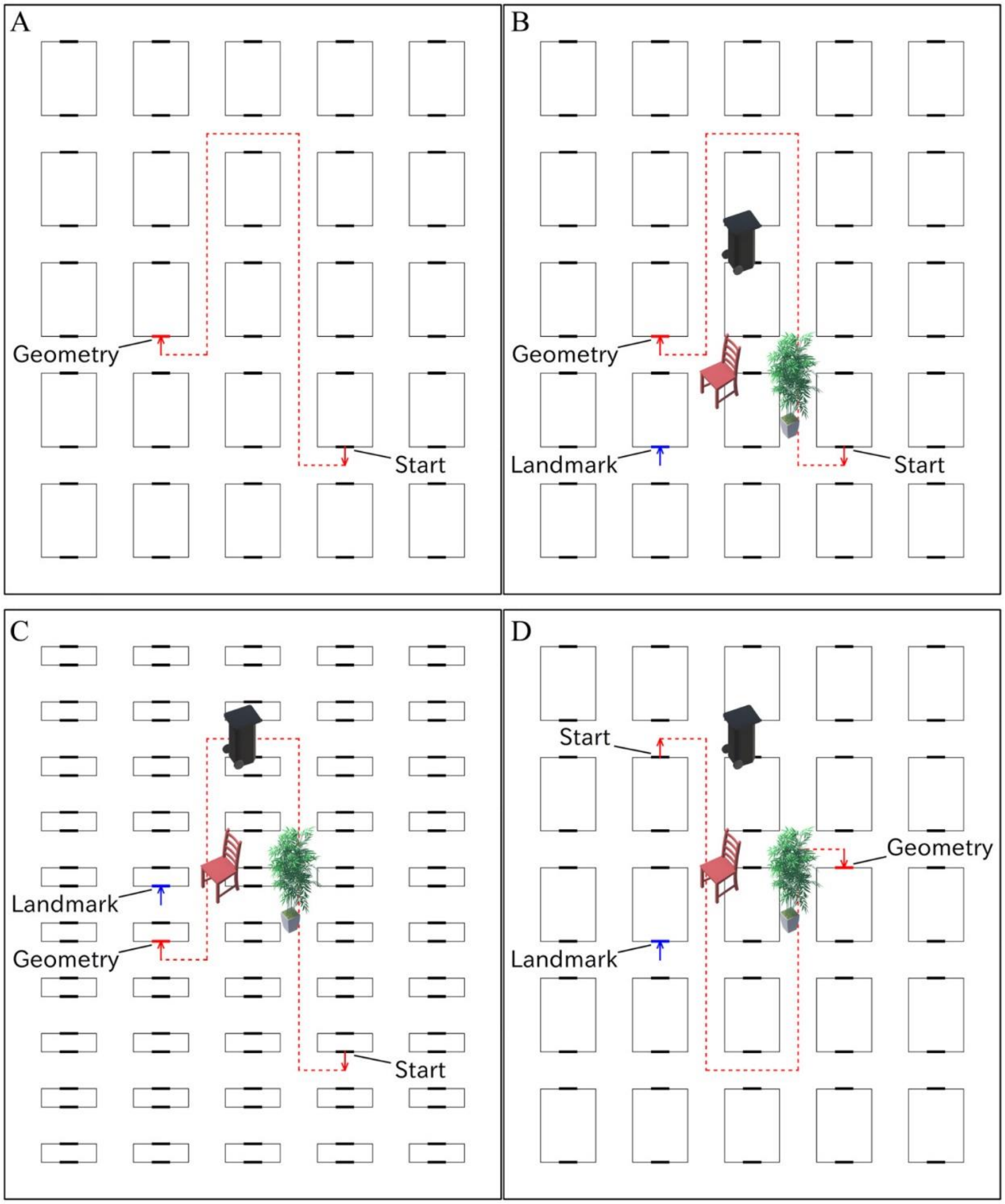

Figure III- 4. Schematic top-down views of the different testing conditions. The red dashed line in each testing trial indicates the route used during the training trials relative to the start location. (A) No Landmarks trials in which the tree, the garbage bin, and the chair were removed. (B) Displaced Landmarks trials in which the landmarks were displaced 1 hallway block south of their original location. (C) Extra Hallways in which extra hallways were added. (D) Different Start Location trials in which the start location was changed. Note that a geometry-based strategy translates to the correct door being rotated 180 degrees relative to training.

Displaced Landmarks. Each landmark was displaced one block south from its original position during training, thus placing the landmarks in a different position relative to training (see Figure III- 4b). The purpose of this test was to examine whether participants would choose a door consistent with the geometric properties of the route (which had not changed) or instead choose a door consistent with the new position of the landmarks.

Extra Hallways. Extra hallways were added in the East-West direction between the existing hallways from training. To add those hallways while keeping the boundary of the environment consistent, we narrowed the walls of each block in the north-south direction (i.e., up-down direction in the top-view) from 3 vu to 1 vu (see Figure III- 4c).The purpose of this test was to examine if participants would use either the overall geometry of the training route or the landmarks to find the correct door when extra hallways were added.

Different Start Location. The start location was moved 180 degrees to a mirror opposite location on the map (i.e., from South-East to North-West) while all the same landmarks retained their original positions, meaning that the last landmark encountered along the route during training (the chair) was now the first landmark encountered (see Figure III- 4d). The purpose of this test was to examine whether participants would choose a door consistent with the geometric properties of the route (unchanged) or instead choose a door consistent with the positioning of the first landmarks encountered.

Final Control Trial. Following completion of all testing trials, participants experienced a final control trial in which the environment was unchanged relative to training and only one door choice was allowed with no verbal feedback provided. The purpose of this trial was to ensure that participants had retained the location of the correct door throughout the duration of the testing phase.

Landmark Recognition Test. To ensure that all participants could recognize the landmarks they experienced during the course of the experiment, a Landmark Recognition test was included at the end of the experiment. Participants were presented with a random series of eight landmarks displayed sequentially on the screen; three were the same landmarks from the experiment and the other five were distracters, and participants had to verbally indicate which landmarks they had seen previously (see Figure III- 5).

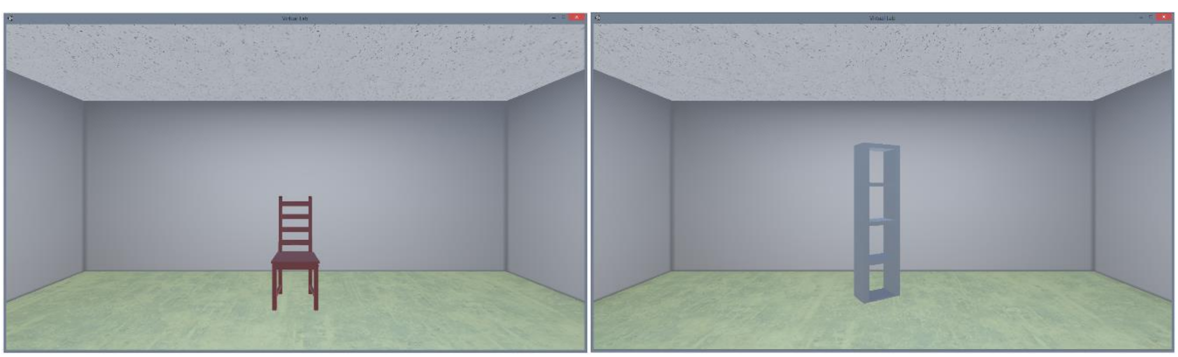

Figure III- 5. Two screenshots of Landmark Recognition trials. The participants saw each landmark individually and responded verbally to the researcher as to whether they saw it during one of the previous trials.

Data analysis

We examined spatial choices made by participants during testing trials. We defined three possible choices participants could make:

Geometry-based: Participants chose the door that was correct based on the geometry of the route learned during training.

Landmark-based: Participants chose the door that was correct according to its position relative to landmarks positioned along the route during training.

Incorrect: Participants chose a door that was not correct based on either the geometry of the route or the landmarks located along the route.

Results

Eleven participants (5 younger and 6 older adults) did not complete the experiment due to dizziness or discomfort from the HMD; ten other participants (5 younger and 5 older adults) were excluded as they did not choose the correct door on the second control trial. Thus, the final analysis was derived from 40 older (20 females) and 40 younger (20 females) adults. Fourteen participants (4 younger and 10 older adults) switched to the laptop display from the HMD after completion of the third training trial if they reported motion-related fatigue.

Head-Mounted Display vs. Laptop Display

To determine if there was a difference between those participants who switched from the HMD to the laptop display prior to testing for each test, we ran eight comparisons (i.e., four testing conditions for each of the younger and older groups). Due to the number of tests, an alpha level of $p < 0.01$ was used as the significance level for all comparisons. Also, due to the smaller expected values (i.e., less than 5) for participants who used the monitor, we employed an Exact Chi-square analysis for each.

The proportion of different choices made participants who used the HMD vs. those who used the monitor did not differ significantly in any of the testing conditions for the younger or older adults (all $p > 0.01$; see Table III- 1).

Table III- 1. Exact Chi-square tests were conducted to examine the difference between participants who used the head-mounted-display and the computer monitor; p-values show that there was no difference in performance based on viewing method.

Test Condition	***p*-values**	
	Younger	Older
No Landmarks	1.000	1.000
Displaced Landmarks	0.607	0.364
Extra Hallways	0.224	0.891
Different Start Location	0.398	0.478

Males vs. Females

To address if there was a difference between males and females for each test, we ran eight comparisons similar to *Head-Mounted Display vs. Laptop Display* above. Due to the number of tests, an alpha level of $p < 0.01$ was used as the significance level for all comparisons. An Exact Chi-Square test was used except for No Landmarks condition, in which a Pearson Chi-Square test was used as the least expected value was greater than 5.

The proportions of the spatial choice between males and females did not differ significantly in any of the testing conditions for the younger, or older adults (all $p > 0.01$; see Table III-2).

Table III- 2. Chi-square tests were conducted to examine the difference between males and females. An Exact Chi-Square test was used except for No Landmarks condition, in which a Pearson Chi-Square test was used; p-values show that there was no gender difference.

Test Condition	***p*-values**	
	Younger	Older
No Landmarks	0.342	0.110
Displaced Landmarks	0.235	0.523
Extra Hallways	1.000	0.844
Different Start Location	0.242	0.413

Testing Conditions

We investigated the types of spatial choices made by participants separately for each group (Younger vs. Older) for each testing condition, combining those participants in each age group who used the HMD and those who used the laptop display. The null hypothesis for each condition was that the type of choices would be randomly distributed. Then, we compared the proportion of choices between the two age groups directly with the null hypothesis being that choice type would not differ between older and younger participants.

To limit the possibility of Type I errors due to the number of tests being conducted, the significance level was set at $p < .01$ for all testing conditions. A Pearson Chi-Square test was used when expected values were at least five or an Exact Chi-Square when they were less than five (see Table III- 3 and Figure III- 6).

Finally, to investigate navigation performance during the final Control trial that was conducted following the completion of all testing trials, we compared the proportion of those who chose the correct door from training compared to those who did not (Pearson Chi-Square test).

Table III- 3. The number of participants who made either geometry-based choices, landmark-based choices, or incorrect choices for each group for each testing condition. Note that participants could not make landmark-based choices during the No Landmarks condition. Numbers in parenthesis indicate those who used the laptop display during testing trials.

Test Condition	Door Choice	Group	
		Younger	Older
No Landmarks	Geometry-based	19 (1)	17 (4)
	Incorrect	21(3)	23 (6)
Displaced Landmarks	Geometry-based	8 (0)	16 (4)
	Landmark-based	31 (4)	23 (5)
	Incorrect	1 (0)	1 (1)
Extra Hallways	Geometry-based	15 (1)	19 (4)
	Landmark-based	20 (2)	12 (3)
	Incorrect	5 (1)	9 (3)
Different Start Location	Geometry-based	11 (0)	14 (3)
	Landmark-based	25 (4)	16 (3)
	Incorrect	4 (0)	10 (4)

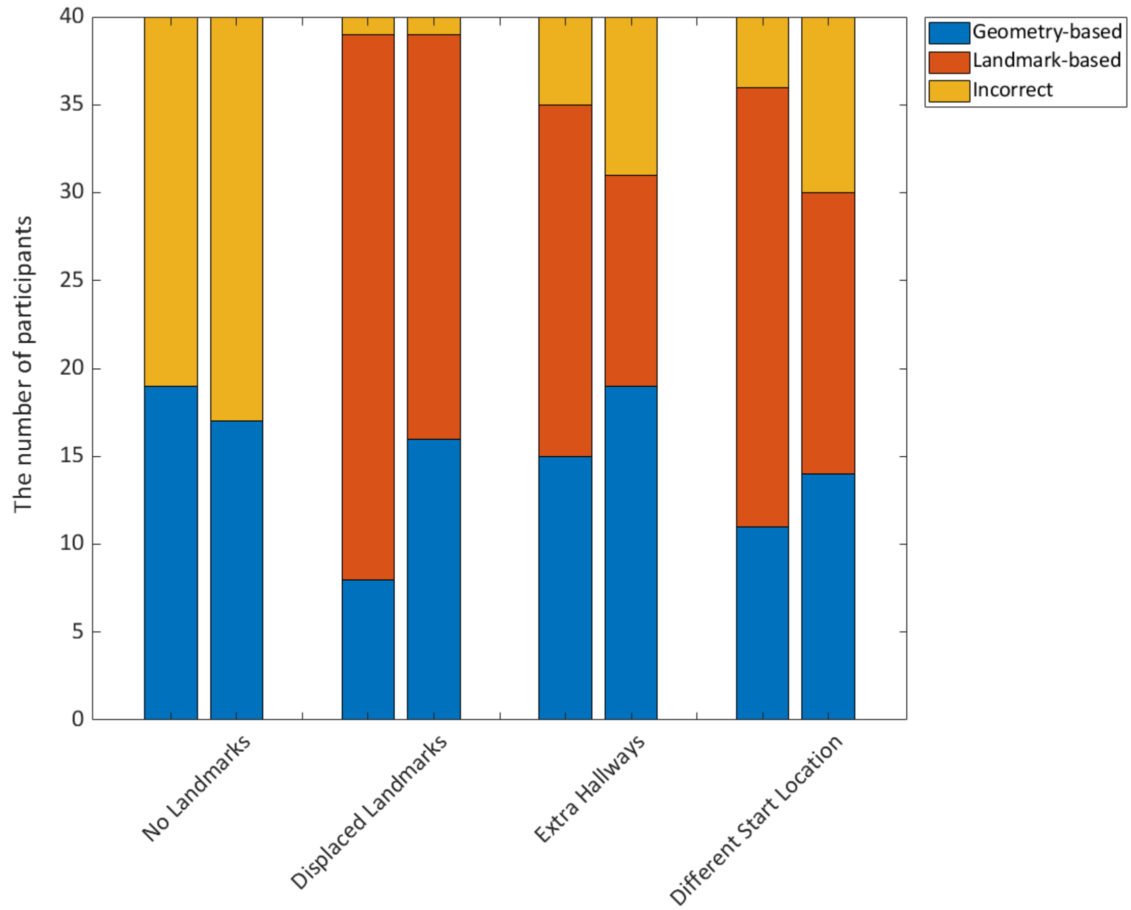

Figure III- 6. The proportion of the participants for each navigation strategy. For each testing trial condition, the left and right columns depict the younger and older groups, respectively.

No Landmarks. Since all landmarks were removed, a choice to the door located in the geometrically correct position along the route was considered the only correct choice and all other choices were incorrect.

Younger Adults: 19 people chose the correct door based solely on the geometry of the route learned during training whereas 21 people chose an incorrect door; this difference did not reach statistical significance at the .01 level (Pearson Chi-Square test, χ^2 (1) = 0.1, p = 0.752).

Older Adults: 17 people chose the correct door based solely on the geometry of the route learned during training whereas 23 people chose an incorrect door; this difference also did not reach statistical significance at the .01 level (Pearson Chi-Square test, χ^2 (1) = 0.9, p = 0.343).

A direct comparison did not show a significant difference between younger and older adults (Pearson Chi-Square test, χ^2 (1) = 0.202, p=0.653). The absolute of effect size |φ| was 0.050, which is considered a small effect [36-38]. Neither younger nor older participants could reliably locate the correct door when only geometric information was available.

Displaced Landmarks. Since all landmarks were present but displaced one block south of their original positions during training, there were two possible correct doors: one based on the geometry of the route and the other based on the position of the landmarks. An incorrect choice was made to any door other than the two described above.

Younger Adults: 8 people chose the correct door according to the geometry of the route learned during training, 31 people chose the correct door according to the position of landmarks situated along the route, and 1 individual chose an incorrect door. The difference among the distribution of choices was significant (Pearson Chi-Square test, χ^2 (2) = 36.95, $p < 0.0005$). Pairwise comparisons showed that the number of landmark-based choices was significantly greater than either geometry-based choices (Pearson Chi-Square test, χ^2 (1) =

13.56, $p < 0.0005$) or incorrect choices (Pearson Chi-Square test, χ^2 (1) = 28.13, $p < 0.0005$).

Older Adults: 16 people chose the correct door according to the geometry of the route learned during training, 23 people chose the correct door according to the position of landmarks situated along the route, and 1 individual chose an incorrect door. The difference among the distribution of choices was significant (Pearson Chi-Square test, χ^2 (2) = 18.95, $p<0.0005$). Pairwise comparisons showed that the number of geometry-based choices and landmark-based choices were each significantly greater than incorrect choices (Pearson Chi-Square test, χ^2 (1) = 13.24, $p <0.0005$; χ^2 (1) = 20.17, $p <0.0005$), respectively. The difference between geometry-based choices and landmark-based choices was not significant (Pearson Chi-Square test, χ^2 (1) = 1.26, $p = 0.262$).

A direct comparison did not show a significant difference between younger and older adults overall (Exact Chi-Square test, χ^2 (2) = 3.852, $p=0.113$). The effect size Cramer's V was 0.219, which is considered a medium effect [36-38].

Extra Hallways. Although the total metric distance of the route remained the same as training, the individual blocks that formed each hallway were shortened. This manipulation resulted in two possible correct doors: one based on the geometry of the route and the other based on the positioning of the landmarks. An incorrect choice was one made to any other door.

Younger Adults: 15 people chose the correct door according to the geometry of the route learned during training, 20 people chose the correct door according to the position of landmarks situated along the route, and 5 individuals chose an incorrect door. The difference among the distribution of choices did not quite reach statistical significance at the .01 level (Pearson Chi-Square test, χ^2 (2) = 8.75, p = 0.013).

Older Adults: 19 people chose the correct door according to the geometry of the route learned during training, 12 people chose the correct door according to the position of landmarks situated along the route, and 9 chose an incorrect door. The difference between the choices was not significant (Pearson Chi-Square test, χ^2 (2) = 3.95, p = 0.139).

A direct comparison did not show a significant difference between younger and older adults overall (Pearson Chi-Square test, χ^2 (2) = 3.613, p=0.164. The effect size Cramer's V was 0.213, which is considered a medium effect.

Different Start Location. This trial was identical to training except that the start location was moved to a location 180 degrees from its training location. A geometry-based choice was one in which participants chose the door that was the at the 180 degree location of the correct door from training. The landmark-based choice was one in which participants simply chose the door closest to the final landmark along the route (the chair). All other choices were considered incorrect.

Younger Adults: 11 people chose the correct door according to the geometry of the route learned during training, 25 people chose the correct door according to the position of landmarks situated along the route, and 4 people chose an incorrect door. The difference among the choices was significant (Pearson Chi-Square test, χ^2 (2) = 17.15, p <0.0005). Pairwise comparisons showed that the number of landmark-based choices was significantly greater than incorrect choices (Pearson Chi-Square test, χ^2 (1) = 15.21, p <0.0005) but did not quite reach significance compared to geometry-based choices (Pearson Chi-Square test, χ^2 (1) = 5.44, p = 0.02). The difference between geometry-based choices and incorrect choices was not significant (Pearson Chi-Square test, χ^2 (1) = 1.26, p = 0.071).

Older Adults: 14 people chose the correct door according to the geometry of the route learned during training, 16 people chose the correct door according to the position of landmarks situated along the route, and 10 people chose an incorrect door. The difference among the distribution of choices was not significant (Pearson Chi-Square test, χ^2 (2) = 1.4, p = 0.497).

A direct comparison did not show a significant difference between younger and older participants (Pearson Chi-Square test, χ^2 (2) = 4.907, p=0.086. The effect size Cramer's V = 0.248, which is considered a medium effect.

Final Control Trial. The navigation performance during the Control trial conducted following testing is summarized in Table III- 3. Only one door was considered correct during this trial whereas choices to all other doors were considered incorrect. Both younger participants (Pearson Chi-Square test, χ^2 (1) = 22.5, p <0.0005) and older participants (Pearson Chi-Square test, χ^2 (1) = 12.1, p = 0.001) chose the correct door more often than the incorrect door (see Table III- 4).

A direct comparison did not show a significant difference between younger and older participants (Pearson Chi-Square test, χ^2 (1) =1.385, p=0.239). The absolute effect size $|\varphi|$ was 0.132, which is considered a small effect.

Table III- 4. Performance of both younger and older participants during the final control trial. Results show that both groups chose the correct door significantly more than the incorrect door. Numbers in parentheses indicate those participants who used the laptop display.

Choice	**Group**	
	Younger	Older
Correct door	35 (3)	31 (6)
Incorrect door	5 (1)	9 (4)

Landmark Recognition Testing Trial. With the exception of one younger adult (who responded with one error), all participants performed perfectly during this trial supporting the fact that participants correctly recalled all the landmarks they saw during the trials.

Discussion

The objective of the current study was to investigate whether the encoding of geometry and features differed between younger and older adults. This was examined through the use of systematic manipulations of the environment, after confirming that the participants learned the predetermined training route.

During training, both younger and older adults learned to search for a correct door located within a virtual hallway complex by following a short, predetermined route; the route included three landmarks and required participants to make turns along the way. Testing trials, in which participants were instructed to locate the correct door when either the geometric properties of the hallways or the landmarks were manipulated, revealed a general finding that both age groups relied more strongly on landmarks to maintain an accurate sense of position. However, younger adults showed an overall tendency to adapt better to the testing manipulations compared to older adults.

Surprisingly, during the *No Landmarks test* when only the geometry of the route was available, both younger and older adults struggled to locate the correct door when relying on geometry alone, with approximately half of them choosing an incorrect door. This finding suggests that both age groups needed at least some landmark cues in order to reliably use the geometry of the route. During the *Displaced Landmarks test*, the landmarks were available but each one was displaced one block south of the original position it had occupied during the training phase, whereas the overall geometry of the route remained unchanged. This manipulation presented two clear strategies for participants; they could choose a door based on following the learned route (geometry-based) or they could choose a door based on the new positions of the landmarks (landmark-based). Results showed that younger participants readily used the landmarks to choose a door consistent with the new landmark positions, while older participants divided their choices between a door consistent with geometry and one consistent with landmarks. Although neither group relied on geometry to any appreciable extent, the younger adults were more likely to adopt a landmark-based strategy whereas the older adults were not, at least when the landmark positions were displaced from the original training route. This finding is consistent with previous research showing that older adults have greater difficulty using landmarks within an allocentric framework [7, 13, 19, 20, 23].

During the *Extra Hallways test* the blocks that formed the hallways were shortened, allowing more blocks to fit within the same distance of the original training route; a geometry-based choice in this context was one made to the door that preserved this exact route distance whereas a landmark-based choice was to a door closest to the final landmark (the chair). Neither group showed any preference for the landmark-based strategy or the geometry-based strategy during this test.

During the *Different Start Location* test, participants started the trial on the end leg of the training route so that the last landmarks they encountered during the training trials (the garbage bin and the chair), were now the first landmarks encountered during the test trial. Participants could choose the door closest to the chair (a landmark-based choice) or continue along the route and choose a door on the opposite side (a geometry-based choice). Results showed that younger adults adopted a landmark-based strategy whereas older adults did not favor either strategy, and collectively made more errors (i.e., choosing doors that were incorrect according to both strategies). This suggests that younger participants' memory for the route may have been more flexible, so that when the order of the landmarks was effectively reversed, they could still recognize the landmark most closely associated with the correct door even though it was always the last landmark they encountered during training.

The fact that younger and older participants could accurately locate the correct door during control trials, when the environment was unchanged relative to training, shows that the environment was sufficiently learned and retained by both groups. However, when changes to the environment still included landmarks, younger participants could use them whereas older participants could not. These results are consistent with previous navigation studies showing that older people perform more poorly compared to younger people when relying on allocentric landmark-based strategies to navigate [7, 13, 19, 22, 23, 39]. Overall, the younger participants in our study seemed more able to adapt to alterations of the environment, providing that landmarks were still available. Neither younger nor older participants could find the correct door using geometric cues alone.

Why might older people form less stable spatial memories of recently learned environments? One possibility is that working memory capacity diminishes with age [40, 41]. Less capacity might not allow the older participants to remember the order of the landmarks along the route, thus it could be difficult to recall during testing trials. Given that our spatial environment was fairly small (only three landmarks), and participants were allowed multiple training trials, working memory load was relatively light during our task. A related possibility is reduced hippocampal volume and corresponding reduction in function as a natural consequence of aging [42-48]. The hippocampus is critical for memory formation, particularly in the integration of the different elements that comprise an event; importantly, it has also been suggested to play a role in working memory maintenance [49]. Specific to spatial memory, the hippocampus is essential since it houses place cells which integrate inputs from cells in nearby cortical tissue that are dedicated to the neural reconstruction of the outside world, which is critical for forming allocentric spatial memories [42, 43, 50]. A reduction in hippocampal volume could prevent encoding the location of each landmark in relation to the target location. Neuroimaging studies have confirmed that increased activation in hippocampal cortical areas are associated with better recall of the spatial layout of an environment [42]. For example, when navigation performance was tested using a virtual Morris Water Maze, younger participants (mean age 26.1 years) outperformed elderly participants (mean age 77.6 years) on measures of allocentric memory (i.e., hippocampal-dependent), with poorer results associated with a corresponding reduction in hippocampal volume as shown via neuroimaging [45].

One concern with our study is the number of people who experienced motion-related fatigue or dizziness when using the head-mounted display; a total of 5 younger and 7 older adults could not complete the experiment, whereas other 4 younger and 10 older adults were able to continue only after switching from the HMD to a laptop display. This is contrasted with previous experiments using the same VRNChair and HMD in which no participants reported dizziness or had to quit the experiment for this reason; the virtual environments used in the previous experiment were either comparatively much smaller (a single room) than the current experiment [5], or large and empty [26, 27]. Due to the space needed for the VRNChair to effectively move the participant within a larger virtual space, the movement translation from real-to-virtual was set at a 1:2 ratio (i.e., a movement of 1 meter in the real world translated to 2 meters in the virtual world). In combination with the relatively narrow hallways of our environment (2 virtual meters in width), some participants may have experienced an unnaturally fast sense of optic flow as a result. However, it must be remembered that participants were able to freely slow their speed down if they felt they were moving too fast. Future studies should address the degree that optical flow speed may contribute to motion-related fatigue in VR environments.

Overall, our results are in agreement with other studies, showing that a general difference in navigation ability between younger and older adults may be one of flexibility [10, 13, 21, 51, 52]. The fact that both groups overwhelmingly chose the correct door during the final control trial shows that the route was successfully learned during training, probably as a combination of encoding geometry and landmarks together. However, younger adults adapted to environmental changes more readily than older adults, and they did this by defaulting to the use of landmarks to guide their choices. Older adults, however, showed more difficulty adjusting to environmental changes, suggesting that their encoding of the route during training was more rigid and resistant to change when compared to younger adults. These results suggest that, as people age, the encoding of spatial information becomes less malleable. The implication is that older adults may have more difficulty remembering previously learned routes in which individual landmarks have either undergone removal or noticeable change. Additionally, they may also find it more difficult to reorient to a known route when it is approached by them from a less well known vantage point.

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Chapter IV. Comparing Young and Older Adults' Navigational Abilities Using a Two-Dimensional Virtual Environment

In the previous chapter, the results overall suggest older adults make more inconsistent navigation patterns than young adults; however, the difference between the two age groups was not conclusive. While the landmarks were remembered well, the geometry itself was remembered by less than half of the participants in each age group. On the other hand, one of our previous studies [53] suggests that older adults produce a greater frequency of error during their search in a landmark-less environment. Thus, the question as whether older adults can learn to encode and rely on geometry of an environment for target finding, remains to be explored; that is the focus of this Chapter.

While the experiments in previous studies (Chapters) were designed in VR, the experiment of this chapter is in a 2D virtual environment as a serious game played on an iPad. Serious games on 2D platforms are much more accessible than in VR settings. Thus, in this chapter, using the available data of a serious game designed for learning integration of geometry of an environment in finding a target [54], we investigated the error type of older adults when searching for a target, while the environment's cues were changed over the trials. We also investigated whether the participants' ability to integrate geometry in their target finding was improved by practice. During each session, featural cues including landmarks were removed gradually to allow participants to rely less on the featural cues and more on the geometry of the environment. This particular spatial game was designed in another study

[54] for training older adults to improve their spatial performance and target finding without relying much on landmarks. *It should be noted that the game and its scoring system were designed for training purpose only and not for assessment or diagnostic; also the training sessions were self-administered.* The author of this thesis was not involved in the game design, and used the data of the older adult participants of that study to investigate whether it can reveal more information of older adults' performance in an environment with focus on learning to integrate the geometry of the environment to find a target. In addition, younger adults were recruited to match the number of the older participants available at the time of analysis to compare their performance.

Do older and young adults learn to integrate geometry while navigating in an environment?

Kazushige Kimura and Zahra Moussavi

Abstract

We evaluated the outcomes of an intervention using a serious game designed to be played on iPads for improving spatial reorientation by training users to integrate geometry of the environment, instead of relying solely on the featural cues. Using data logged online through a clinical study of using this game, the effect of training among 16 older adults (69.3 ± 6.4 years, 4 males), who played the game repeatedly (self-administered) over a period of 8 weeks, was investigated. The game contains a hexagonal room with 3 objects, textured walls and grids on the floor, which are removed one by one as the participant played the game. In each level, the room also rotates such that the view point of the user is different from that of the previous level. Participants cannot play a higher level unless they make no mistake during the trials of the lower test level successfully. In addition to data of older adults available from that clinical trial, we also recruited 16 young adults (27.3 ± 5.6 years, 4 males) to play the game for 5 sessions and compared their results with those of the older adults. We evaluated the error type made in each test level, and the scores for each session among older adults. Further, we compared the frequency of each error type between young and older adults during the test levels that a landmark adjacent to the target was removed over the first 5 sessions. The results of older adults' performance suggest they

learned to make less mistakes over the sessions. Also, both young and older adults learned to integrate the geometrical cues rather than relying on the landmark cue adjacent to the target to find the target. Overall, the results indicate the designed hexagonal room game can enhance spatial cognition among all age groups of adults.

Keywords: Serious game, Aging, Spatial cognition, Landmarks, Geometry

1. Introduction

Serious games are designed to engage participants' interest to a task for testing some hypotheses [1-4]. Although experiments not employing gamification element also allow researchers to investigate their hypotheses [5-8], several studies show that engagement in the game improves participants' performance during the experiments [9-12]. These games have been used not only for education [13-15], but also for enhancing human skills such as working memory, executive function and cognitions [16-23]. While there are numerous numbers of studies reporting on improvement of working memory and executive functions after an intervention [16-20, 24-34] (see reviews [35, 36]), the effect of training with a serious game on spatial cognition has received relatively less attention. Nevertheless, studies suggest that spatial cognition is commonly enhanced by repeated exercises of some serious games [16, 19, 21-23, 37, 38]. These studies employed tasks that had an independent outcome measure than what was practiced. Examples of such tasks include mental rotation [16, 37] and multi-domain task that contained navigation and memory/executive functions [19, 38] to investigate the effect of an intervention; both near and far transfers are reported. However, the process of gaining the abilities to perform better during the training program involving navigation remained unaddressed.

Investigating human spatial cognition across different age groups is crucial for better understanding of aging effect, particularly during learning a new task. Previous findings suggest that aging leads to a decline in spatial cognition during wayfinding and route learning tasks [39, 40]. An example is Morris Water Maze test that trains participants (or animal subjects) to learn the location of a hidden target before probe trials; during the probe trials, the target is completely removed, and the quadrant of the environment that participants (or animal subjects) spend their time most is examined [41-43]. This test is widely used as an independent outcome measure in spatial training programs.

To address the decline associated with aging, researchers have also designed experiments to investigate individuals' navigation performance during testing phase that the environment is manipulated. Another example is Reorientation paradigm that manipulates either geometry (e.g., the shape of the environment, or the proportion of wall lengths) or feature (e.g., landmarks or colour of wall) to test which one plays more important role in recovering direction [44-47]. The research outcomes of these studies commonly suggest that older adults require a greater number of training trials to learn the location of the target, and they make the more mistakes during testing phases [39, 48].

In the above-mentioned studies, the learning phase following by a control trial is to ensure that the participants have learned the task, whereas the testing phase is to address the research question. On these studies, the frequency of mistakes (errors) were investigated along with the duration and total traversed distance [43, 49]. However, the type of the mistakes that participants made during the experiments was not investigated or reported. Investigating the error type may hint participants in different age groups rely on what type of cues (geometrical versus featural) more often and whether they can learn to integrate the geometry of the environment. Our previous study [50] showed that the older participants (50-86 years old) could distinguish the objects they observed during a navigational task from the objects they did not observe; though, not all of the older adults remembered the geometrical component of the environment. Another study suggested older adults preferred to use non-geometrical (i.e., featural) cues [51]; however, which of the non-geometrical cues was preferred most, and whether the older adults could learn to integrate the geometrical cues were not clear. A study using a maze experiment showed that the participants remembered the landmarks placed at decision making point (e.g. an intersection to make a turn) better than those placed at non-decision making points (e.g. between intersection) [52]. Moreover, older adults made more errors than young adults during their search for the target's location in a landmark-less environment [53].

In a recent clinical trial study [54], a series of serious games designed as an app for iPads was used to train older adults; one of the games was a 2D spatial game. This game was designed to improve people's encoding of geometrical cues rather than the landmark adjacent to a hidden target to find the target in a hexagonal shape room. The view point of the subject changed in each trial and the landmarks were removed one by one. As the goal of the games were training and not assessment, there was also a hint button that could be used by users to highlight the target by flashing the tile of its location; the usage of the hint button had a penalty score but could be used as often as a user wished. In addition, if users made mistakes more than three times, or pressed the hint button, the trial was repeated exactly the same until they find the target without any mistake and using the hint. In this study, we used performance data of that hexagonal room spatial game and investigated three hypotheses: 1) the older adults remember a landmark located next to the hidden target better than other landmarks located far from the target, 2) the older adults can learn to integrate geometrical cues rather than relying solely on the landmark located next to the hidden target by repetition and training, and 3) the young adults learn to integrate the geometrical cues rather than relying solely on the landmark next to the target, quicker than the older adults.

2. Methodology

In this study, we used the available data that was logged during a self-training program as part of a clinical trial [54] on the effect of self-administered cognitive brain exercises through a series of serious game. The cognitive exercises included 7 different games, out of which one was designed for improving spatial cognition; in this study we used performance data of only that game. The spatial game's environment and its scoring system are described below.

2.1 The Spatial Game Experiment

The spatial game's environment is a 2D view of a hexagonal virtual room with tiled floor developed for iPads, in which the participants are instructed to find a hidden target tile by dragging an avatar on the screen (Fig. IV- 1). Once the avatar is dragged to the target tile in one move (without stopping at different tiles), the avatar goes back to the start location and the target tile is highlighted with an awarding sound as shown in Fig IV- 1(b).

(a) (b)

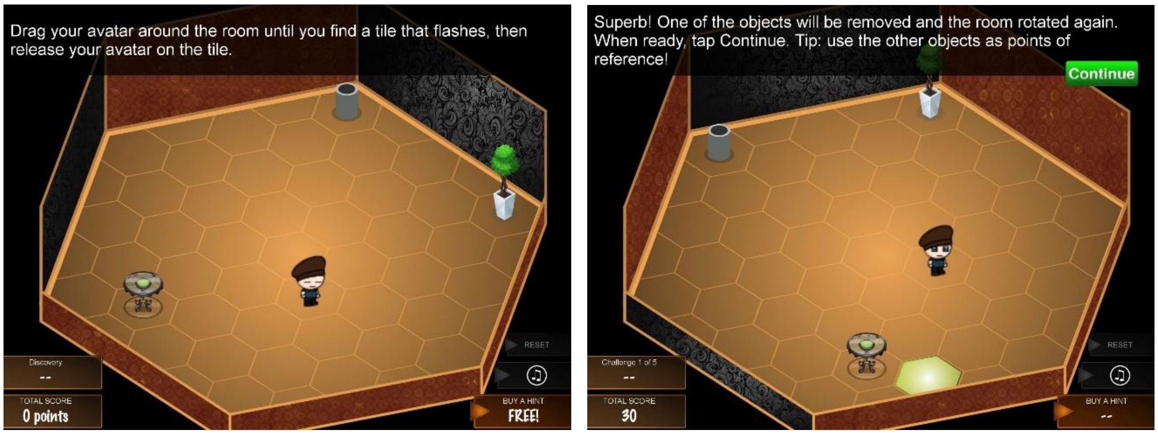


Figure IV- 1. Screen captures of the spatial game. The environments presented in (a) and (b) are identical, except the angle of the camera. Note that the target tile is highlighted once it is found, as shown in (b).

Users observe the environment from a third-person-view. The game has been designed for iPads because most older adults use iPad versus android devices; also touch-screen feature of the game coordinates users' vision and what they want to point out enhancing user experience [55]. Thus, users would be more engaged in the game compared to employing a mouse or a keyboard in navigation with 2D desktop virtual environment, which would require familiarization [56-58].

The target tile is assigned to either of the two tiles located in front of center of a wall. As the room contains six walls, there are twelve possible tiles, and the target tile is assigned among those tiles randomly. Within the environment, there are three landmarks: one is placed adjacent to the target, and other two are placed farther such that all the landmarks are distributed across the environment evenly (see Fig. IV- 1(b) as an example of landmarks locations). Tiles with a landmark and half tiles adjacent to each wall are not used as target tiles. Figures IV- 1(a) and 1(b) show first two trials of the game, in which only the view point of the player has been changed by a simple clockwise rotation. After that if the user finds the target tile without stopping at different tiles, one of the landmarks are being removed and the room is rotated again too.

The program tracks the tile that players choose, and records it as correct or erogenous with a score (described in Scoring System section). The errors are further grouped into 3 types: Nearby Error, Nearby Corner Error, and Side Error as shown in Fig. IV- 2. To understand the error type, consider dividing the entire room into 6 equal segments by the red lines as shown in Fig. IV- 3. Assuming the target is the green tile in Fig. IV- 3, Nearby Error is when a tile in the adjacent tiles of the target's segment (i.e., the blue tiles in Fig. IV- 3) is chosen. Nearby Corner Error is when either of the four tiles that crossed the segment containing the target and the adjacent segments (i.e., the yellow tiles in Fig. IV- 3) is chosen. Side Error is when other tiles (i.e., the white tiles in Fig. IV- 3) are chosen.

Figure IV- 2. A screen capture of the hexagonal room with arrows indicating types choices: The green, blue and yellow arrows indicate the Correct (i.e., target tile), Nearby Errors and Nearby Corner Errors, respectively. The ones without an arrow indicate Side Errors.

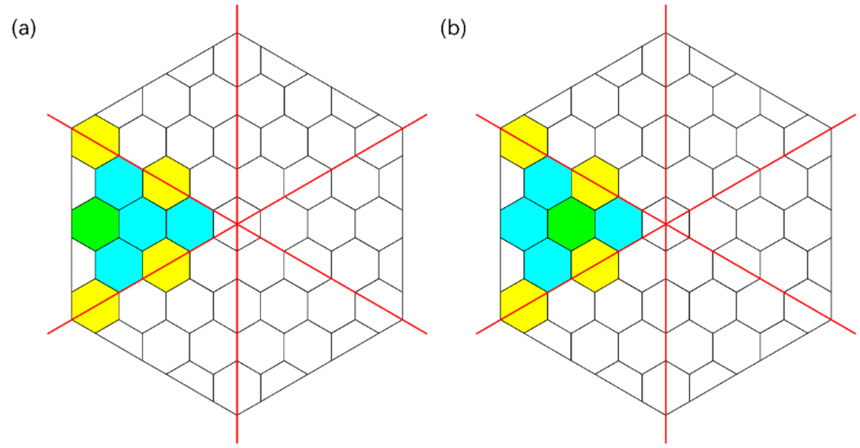


Figure IV- 3. Top-view of our hexagonal room environment. In each of the 6 equal segments of the room, a target tile is either besides the middle of the wall (a), or one tile closer to the center of the room (b). Assuming the Green tile is the target tile, the 3 error types are shown by color: Nearby Error with blue, Nearby Corner Error by yellow, and Side Error by white color. The red lines are to visualize segmentations purpose, and invisible during the game.

A session of the game consists of 6 different levels of training and 5 test levels. The order of these levels is fixed. During a session, the avatar is always located at the same tile at the beginning of each level, and the players are asked to find the target that its location is fixed across the levels. The angle and the position of the camera is randomly changed between the levels. Thus, the absolute position of the iPad's screen does not help the players to find the target.

Training Trials – At the very first training trial, players are asked to drag the avatar around the room until they find a tile that flashes, then release the avatar on the tile, and learn (encode) the location of the target tile. The environment initially at the start of the game contains 3 landmarks, 6 textured walls, and grids shown on the floor. During this first training trial, no point or penalty is assigned; thus, players can freely search for the target tile. Upon finding the target tile, a flashing light is displayed and rewarding audio is played. Then the trial is repeated to ensure that they encode where the target is; this repeated training trial is served as a control trial. After this very first training and control trials, when a player makes a mistake, and cannot find the target during or before the third drag, the target tile is highlighted, and the trial is repeated; then, the trial will be repeated until the player drag the avatar to the target tile with no mistake. There is no limit on the number of times that a trial will be repeated, while there is a penalty score associated with mistakes after the very first training trial. As the goal of the game is training (not assessment), the trial at the same level will be repeated until the player makes no mistake. Only after a trial with no mistake (also called a control trial) the player will be presented with the next challenge (next level trial).

Test Trials – Test trials are the trails at every different level that challenge the player with a new perturbation (e.g. rotation of the view point, removing objects, etc.). The game has five levels to train players to encode the environment by integrating geometry rather than relying on the object next to target solely; the game is designed to strengthen the integration of the geometrical cues of the environment. The first test level is only rotation of the room, during which the environment is rotated by placing the camera at another position; in other words, only the viewpoint of the player changes. The second test level is rotation and one landmark removal, during which the environment is rotated, and the landmark adjacent to the target tile is removed (see a table in Fig. IV- 1(b)). The third level is rotation and two landmarks removal, during which the environment is rotated and one of the remaining 2 landmarks is removed. The fourth test level is rotation and texture removal, during which the environment is rotated, and the texture of the walls is removed; all walls of the room at this level have only one of the three textures; the choice of the texture is randomized between the sessions. The last test level is rotation and grids removal, during which the environment is rotated and the grids (the tiles) on the floor of the environment are removed. See Table IV- 1 for a summary of changes across the test levels.

Table IV- 1. The difference across the test levels.

Test Level	**The number of landmarks available**	**Texture of the walls**	**Grids on the floor**
Rotation only	3	Not changed	Available
Rotation and one landmark removal	2	Not changed	Available
Rotation and two landmarks removal	1	Not changed	Available
Rotation and texture removal	1	Uniformed	Available
Rotation and grids removal	1	Uniformed	Removed

The order of the levels is fixed across the sessions; as a player proceeds in the game, an extra spatial perturbation is added for each level. The degree of the rotation (i.e. ±60, ±120, ±180 degrees) is selected randomly between the levels. Within each level, however, the degree of the rotation is fixed when a player makes mistakes and trials are repeated. Similar to the training level, trials for each level are repeated until a player makes no mistake. In other words, when a player makes no mistake during the first trial of each level, a player receives only 1 trial, and proceeds to the next test level. For each level, the target tile is highlighted when a player makes mistakes and cannot find the target during or before the third drag.

Scoring system – Upon passing a training trial with no mistake (i.e., a control trial), always 5 points are allocated regardless of the frequency of incorrect choice were made before. During each of the test levels, a total of 25 points are allocated at the beginning; players obtain a score between 5 and 25 points depending on their performance within the level. Penalty (i.e., deduction of the score) for dragging the avatar to one of the incorrect tiles (i.e., making error) is defined as following: Each of the Side Error, Nearby Error and Nearby Corner Error has penalty scores of -5, -2, and -1 point(s), respectively. A trial is repeated until a player drags the avatar to the target tile with a single move (no error) during the trial. The points are calculated across the trials within a level. As an example, a score of 19 points is given for a level, when a player makes a Side Error during the first trial (-5 points), a Nearby Error (-1 point) during the second trial, and no errors during the third trial within the same level. If the score is less than 5, the players are given a minimum of 5 points at the end of the level to encourage them to proceed to the next level. During each session, with a training and 5 tests levels, the maximum and the minimum possible scores are 130 and 30 points, respectively. The difficulty levels and scoring system were designed to train players to encode an environment with special focus on learning to integrate the geometrical cues rather than featural cues of the environment solely in order to enhance their reorientation skills in any new environment.

2.2 Study Participants

Data of 16 older adults (69.3 ± 6.4 years, 4 males) who participated in the clinical trial of the application [54] were used in this study. The older adults played the game over a maximum period of 8 weeks up to 83 sessions (varied among the participants – see Table

IV- 2 for details) at their own pace as they were doing it at their home (part of the clinical trial design [54]). In addition, 16 young individuals (27.3 ± 5.6 years, 4 males) were recruited, and were asked to play the same game for 5 sessions in one day. The reason for a different protocol for young adults was mainly time constraint and difficulties in recruitment as the designed games were for older adults and would be boring for young adults. We chose 5 sessions per one day as overall young adults master games quickly.

Both groups' performances in the spatial game were analyzed. No participant was paid as a compensation of participating this study. All participants signed a consent form approved by the Biomedical Research Ethics Board of University of Manitoba prior to their participations. All study participants observed a demonstration of how the game should be played by a tutor. During collecting data, no supervision or help was provided to the participants.

Table IV- 2. The number of the older participants over the sessions.

The number of sessions	The number of the older participants
5	16
10	14
15	12
20	10
25	8
30	7
35	6
40	5
45	5
50	5
55	4

2.3 Data Analysis

First, we investigated whether the older adults overall learned to find the target tile as the game's level was increased gradually over the sessions; for that, we compared the average total scores of the older adults over the sessions. Next, we investigated the frequency of each error type for each test level during the first and the last 3 sessions of the older adults, and compared them to the total score of each test level. As the older adults played at least 7 sessions, no overlapping session existed when the first and last 3 sessions were compared. These comparisons allowed us to highlight which error types changed under which test levels by practice over the sessions. Finally, we investigated whether the older adults learned to encode the environment differently from the young adults by comparing the error distributions between the two age groups during “Rotation and one landmark removal” level of the first 5 sessions. In other words, we investigated if there were a difference between the age groups at that level. We employed Repeated measure ANOVA with Greenhouse Geisser correction for the first two investigations, and Chi-square test for the last investigation.

3. Results

3.1 Average scores over sessions

Figure IV- 4 depicts the average scores of the older adults over the sessions. The higher scores indicate that the participants learned to find the target tile with a lesser frequency of errors. The maximum possible score of the game was 130. Note that the number of participants over the sessions were different because it was a self-training program and therefore participants played the game different number of sessions and days.

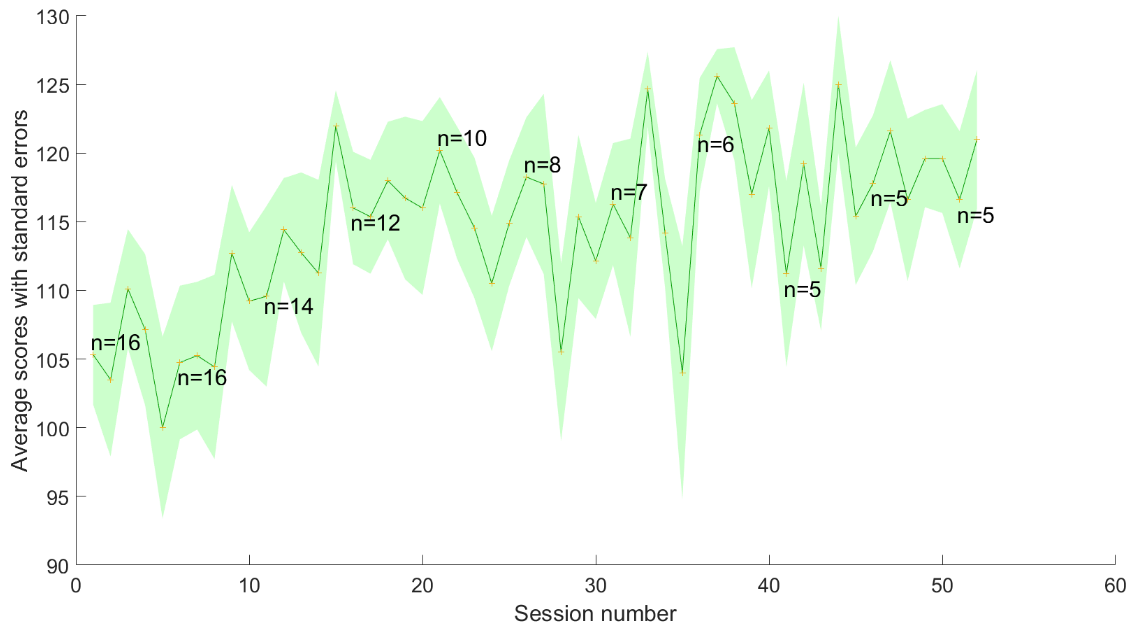


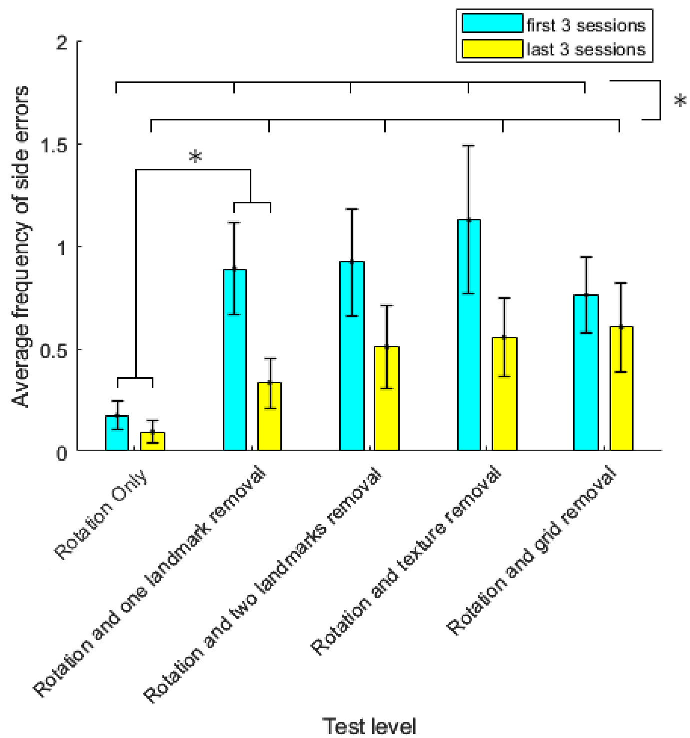
Figure IV- 4. The average scores of the older adults. The solid line presents the average and the shaded area presents the standard error of the scores for each session. The number n presents the number of participants whose data were available at that session.

Among the older adult participants, we observed a gradual improvement in the scores over the first 20 sessions, and then almost plateaued. The Repeated measure ANOVA did not show a significant change of the scores ($F(3.350, 13.398)=1.646$; $p=0.224$), meaning that the overall performance did not improve significantly over sessions. However, particularly after the 15th sessions, the scores were better than those during the first several sessions. The findings suggest the older adults eventually learned to integrate the geometry of the environment, rather than relying solely on the featural cue that was placed adjacent to the target location of the environment to find the target tile.

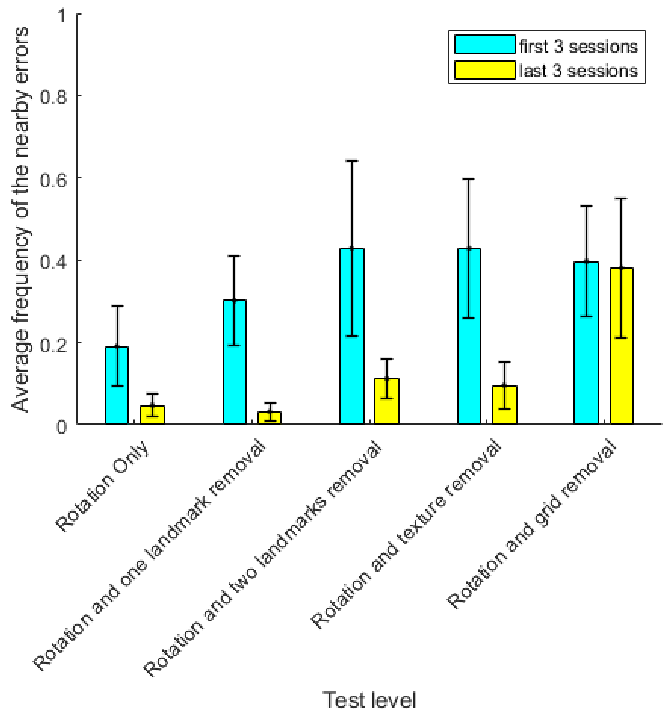
3.2 Errors between the first and the last 3 sessions of each participants

Next, we investigated the error type during each test level over the first and last 3 sessions. Figure IV- 5 (a, b, and c) compares the scores of the first and the last 3 sessions of the older adults. On average, all error type decreased after participating several sessions.

(a)



(b)



Average frequency of the nearby errors
1
0.8
0.6
0.4
0.2
0
first 3 sessions
last 3 sessions
Rotation Only
Rotation and one landmark removal
Rotation and two landmarks removal
Rotation and texture removal
Rotation and grid removal
Test level

(c)

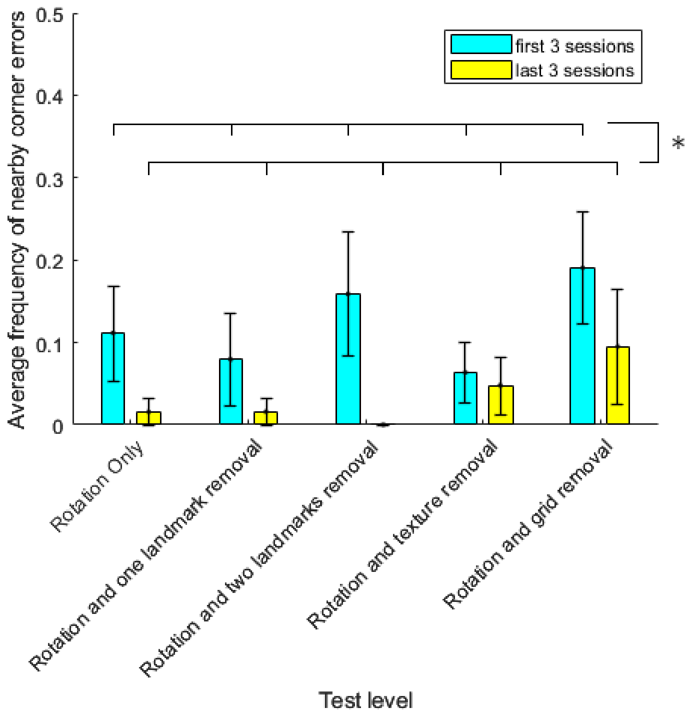


Figure IV- 5. Comparisons of the average frequency of (a) Side Errors (b) Nearby Errors, and (c) Nearby Corner Errors of each test level made by the older adults. The blue and yellow ones show the average frequencies during the first and the last 3 sessions respectively. The error bars represent standard errors.

For Side Error type, a two-way Repeated measure ANOVA did not reveal significant interaction term between the sessions and test levels ($F(2.493, 44.138)=0.972$, $p=0.413$), but revealed significant main effect of the sessions ($F(1,15)=5.371$, $p=0.035$), and test levels ($F(2.240, 33.595)=3.525$, $p=0.036$). The pairwise comparisons showed significant difference between "Rotation only" and "Rotation and one landmark removal" test levels. The older adults made Side Errors less frequently during the last 3 sessions than the first 3 sessions, and more frequently during “Rotation and one landmark removal” test level than “Rotation only” level; that was expected as there are two perturbation in the latter condition.

For Nearby Error type, a two-way Repeated measure ANOVA did not reveal any significant term for interaction between the sessions and test levels ($F(2.148, 32.219)=1.69$, $p=0.198$) and main effect (sessions: $F(1,15)=3.637$, $p=0.076$; test levels: $F(2.678, 40.176) = 1.853$, $p=0.158$). The frequencies of the Nearby Errors during the first and last 3 sessions, and across different test levels did not differ statistically.

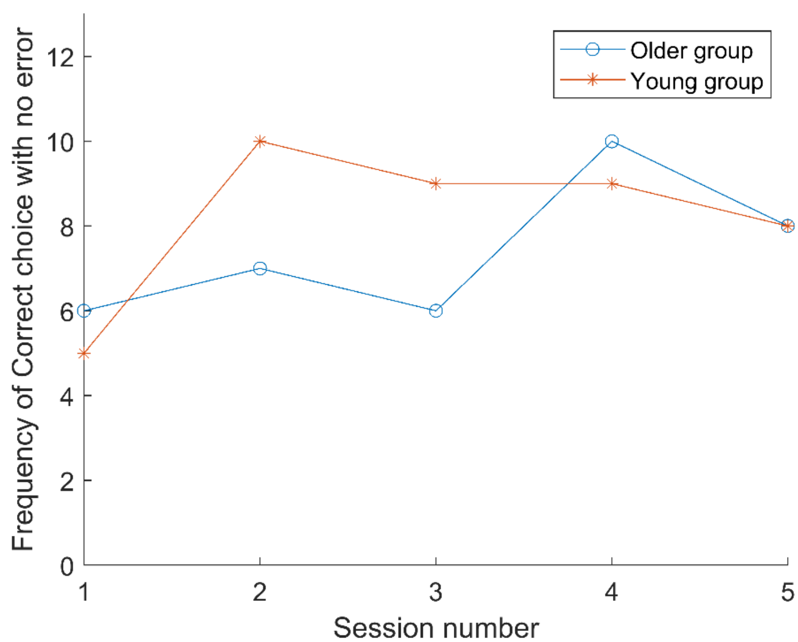
For Nearby Corner Errors, a two-way Repeated measure ANOVA did not reveal significant interaction between the sessions and test levels ($F(2.112, 31.680)=1.078$, $p=0.355$) and main effect of test levels ($F(2.030, 30.453)=1.732$, $p=0.194$), but revealed significant main effect of sessions $F(1,15)=7.857$, $p=0.013$. The older adults made Nearby Corner Errors less frequently during the last 3 sessions, compared to that of the first 3 sessions.

Altogether, these results suggest that the older participants learned the correct segment by reducing the Side Errors; they also learned the location of the target within the correct segment by reducing the Nearby Corner Errors. As “Rotation and one landmark removal” was the first test level that the participants had to stop relying on the landmark to find the target within a session, we also investigated the error types distributions of this test level between the two age groups. We compared not only the Side Errors, but also the other error types over the first 5 sessions.

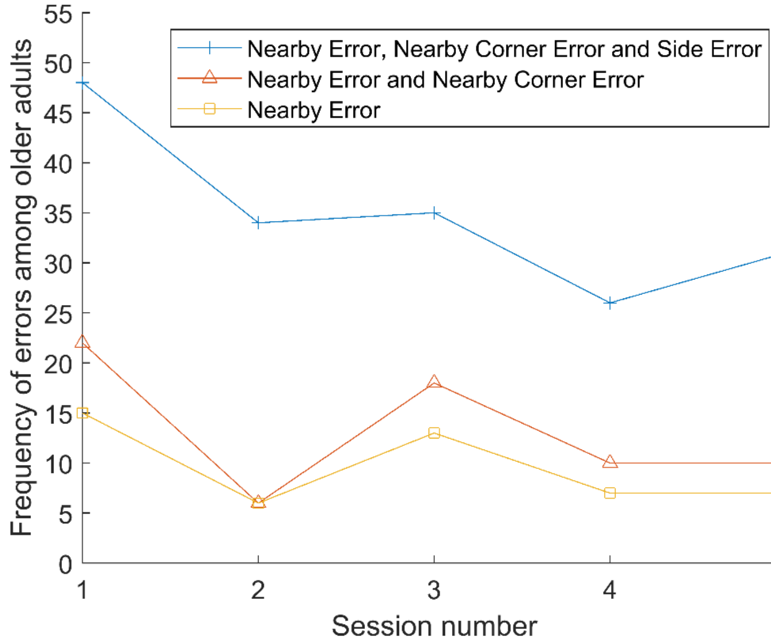
3.3 Errors during the first 5 sessions of "Rotation and one landmark removal" level between the young and older adults

Figure IV- 6 depicts the frequencies of participants who made zero error, and each of the Side Errors, Nearby Errors and Nearby Corner Errors during "Rotation and one landmark removal" level over the first 5 sessions. Fig. IV- 6(a) shows the frequency of the zero error (i.e., the number of the participants who did not make any mistake). By contrast, the second and third plots show the frequencies of errors of older and young adults, respectively. As can be seen, the number of zero error at this level increased, while the Side, Nearby and Nearby Corner errors decreased during the sessions in both older and young adults. This suggests both age groups learned to find the target without relying on the landmark adjacent to the target in the first 5 sessions.

(a)



(b)


Nearby Error, Nearby Corner Error and Side Error
Nearby Error and Nearby Corner Error
Nearby Error
Frequency of errors among older adults
Session number
0
5
10
15
20
25
30
35
40
45
50
55
1
2
3
4
5

(c)

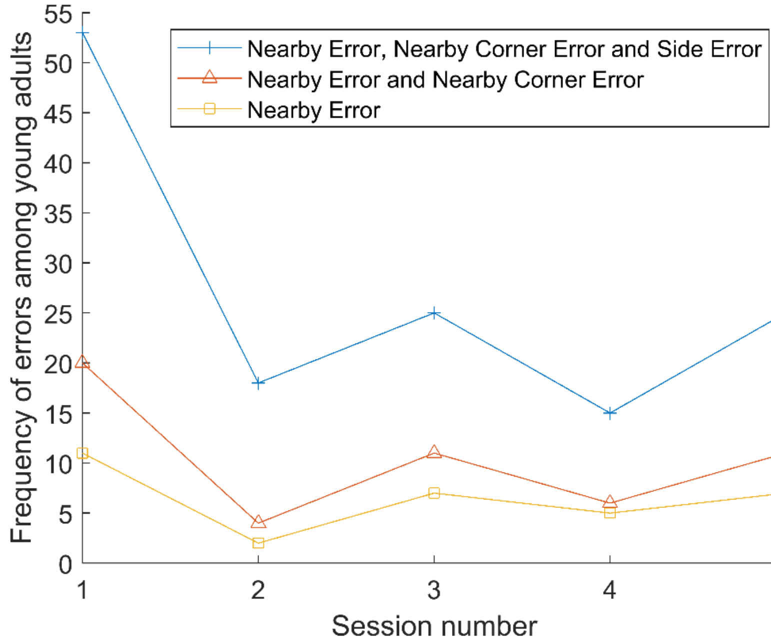


Figure IV- 6. Frequencies of (a) correct choice with no error, (b) Nearby Error, Nearby Corner Error and Side Error over among the older adults and (c) those among young adults during the first 5 sessions at "Rotation and one landmark removal" level.

Chi-square tests did not reveal significant difference in the frequencies of the errors (including zero error) between the young and older adults during the first five sessions ($\chi^2(3)$ = 0.655, 0.064, 0.523, 0.805, and 0.816 for first to fifth session, respectively).

For the older adults, the frequency of the Side Error reduced after the third session. It indicates that they still relied on the landmark adjacent to the target tile during the second session. Within the correct segment, they reduced their frequency of errors (i.e., the Nearby and Nearby Corner Errors) during the second session. In terms of the correct response without making any mistake, they showed a slower improvement; the number of participants who did not make any mistake increased during the fourth session.

On the other hand, the young adults showed a greater frequency of the errors, particularly the Side Errors during the first session. However, by the second session, the frequency of their errors reduced much more than that of the older adults. Also, it should be noted that a greater number of the young adults made a correct choice without making any mistake during and after the second session. This indicates that the young adults improved their performances quicker than the older adults did.

4. Discussion

Overall, through practicing with the spatial hexagonal room game, the older adults improved their performances by learning how to find the target under different test levels over self-administered sessions. A major limitation of this study has been the small number of study participants; as it was self-administered and there were more games than the spatial room in their intervention, only 16 older adults completed more than 5 sessions of the spatial game. In addition, since the older adults of this study played the game at their own pace with no supervision, it is possible that at some sessions, they have had some distraction. That plus the small number of samples could be the reason to for the fluctuation or a decrease in scores in some sessions, especially during the 28th and 35th sessions shown in Fig. IV- 4. It should be noted that the numbers of the participants in those two sessions were 8 and 6, respectively. Some participants did not play more than 15 sessions. Thus, the decline in those two sessions does not mean the participants declined their performances after some point. In fact, overall the average scores were consistently above 110 (out of 130 max) except in those sessions, whereas the average scores during the sessions before the 10th session were below 105. As the difficulty level of each session for each participant differed, averaging every 5 sessions can probably contrast the learning effect in a better way; Figure IV-7 depicts the average scores for each 5 sessions.

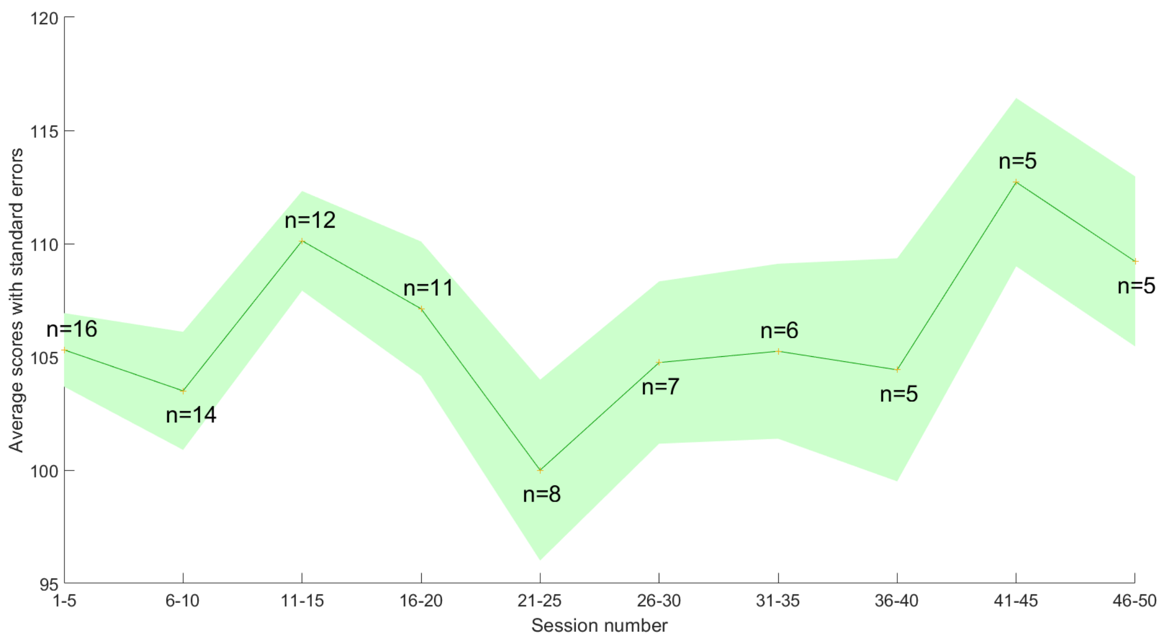


Figure IV- 7. The average scores for each 5 sessions of the older adults. The solid line presents the average and the shaded area presents the standard error of the scores for each session. The number n presents the number of participants whose data were available at that session.

With regards to the reliance on featural cues during the first test level that the environment was simply rotated, players still could not rely solely on the landmark adjacent to the target that gives a strong clue for the location of the target tile. A player had to identify the direction of the target relative to the landmark. Therefore, this hexagonal room game, including its “Rotation only” level, may serve as a training tool for participants (older adults in particular) to integrate the geometry of the environment to find a target.

We investigated the frequency of each error type, and whether they were reduced over the sessions. Interestingly, the frequency of errors did not reduce within the “Rotation and floor grids removal” test level (last and highest test level). This suggests the participants learned to integrate the geometrical components (and not relying on landmarks only) after several sessions, but they could not learn to locate the target tile without the grids. It is possible that the users who reached this level were relying on counting the tiles with respect to the geometry of the environment to find the target. Thus, when the grids were removed their counting cue was perturbed.

In a future study, we should address how counting the grids would help to find the target, and would change a navigation strategy. During the “Rotation and floor grids removal” test level that removes the grids on the floor, a very slow dragging of avatar can still reveal the grids pattern because the movement of avatar looks jumpy between the hidden tiles; thus, it is possible some used this strategy to still count and find the target. More importantly, grouping error types does not allow to evaluate players’ localization performance with a finer granularity. To overcome this shortcoming, the trials of the last test level should be replaced such that the avatar moves continuously regardless of the tiles’ pattern employed during training level to allow participants to estimate the target tile location; we can then measure Euclidian distance between the target location and the location that they think is correct.

As for the comparisons between the two age groups, the young adults made a greater frequency of mistakes initially. Perhaps the young adults preferred to use the landmark adjacent to the target tile to locate the target during the training level and did not pay attention to encode the environment for geometry integration; for them it was only a game while for older adults it was a training too. Also, the older adults might have a greater number of the trials during the training level to encode the location of the target. It worth to note that the protocol differed between the older and young adults in terms of the number of the sessions per day. The older adults played two sessions per day on average, whereas the young adults played five sessions in one day only. Since the location of the landmarks, combination of textures, and relationship between the start and target tiles differed for each session, we assume that the carryover effect for the older adults did not differ from that for the young adults. All of the older adult participants were enrolled into a training program and they desired to excel by practice. On the other hand, the young participants were confident of their spatial skills and participated in the study only for a day for a research curiosity. Thus, it can be expected that young adults were careless and faster in their initial moves in the game compared to older adults. Nevertheless, another study suggests older adults require both geometrical and featural spatial components to locate the target [50]. Therefore, before proceeding to the test levels, the young adults might have learned the featural cues (i.e., landmarks) alone, whereas the older adults learned the geometrical component as well. This could explain the greater frequency of the errors during the very first trial that the participant could not rely on the landmark. After the first session, however, the young adults learned to reduce the frequency of mistakes quicker than the older adults. In other words, the young adults learned to integrate the geometry of the environment more effectively than the older adults, suggesting the greater amount of flexibility in their navigation strategy.

The presented study required participants to mentally rotate the environment to locate the target tile as the camera position changed. This task needed to combine both the feature and geometrical available cues; this is an ability required to solve mental rotation task and has been reported to decline by aging [59, 60]. The observations that the older adults reduced the frequency of error during the test levels suggest that they were able to learn and enhance their spatial skill; that is indeed encouraging. To address whether they improved beyond the practiced game, a future study should employ another independent mental rotation assessment, and investigate correlation of the performances between the presented game and that mental rotation assessment.

Integration of the cues available during the training level resembles the ability tested by Morris Water Maze task, during which older adults showed a decline in their performance [42, 43, 61]. Namely, it was reported that older adults learned a target's location with a longer traversed distance [51]. Thus, a comparison of the performances between older and young adults during training trials should be investigated in a future study as well. Currently, the game does not log the number of times a level is repeated; it only logs the scores. Particularly during and after the second session, older adults may exhibit difficulties in finding the target with a greater number of trials required during the training level before proceeding to the test levels.

Aside from the small sample size of the study, another limitation of the current study is the duration and number of the sessions. Since the protocol of the study using the spatial game was self-administered, each participant played a different number of sessions (see Table IV- 2). On the other hand, the young adults, who were recruited in the present study for comparison, played all 5 sessions within a day. These may lead to different learning outcomes for participants of the two age groups. Future studies should address these limitations by having a controlled and supervised number of sessions over a fixed period of time.

5. Conclusion

We demonstrated that the designed serious spatial game using a virtual hexagonal room has potentials to be used as a training tool to enhance the use of geometrical components of an environment. Although the young adults learned and adapted faster, the results show that the older adults also learned to integrate the geometrical component into target finding over 15 sessions. Overall, all participants, particularly the older adults, found the designed game easy to use, engaging and beneficial to their orientation skills in general.

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Chapter V. Conclusion

5-1. Summary of findings

A series of experiments using VR technology to understand human spatial cognition were performed. A study comparing immersive virtual and real environments was presented in Chapter 2 [1]; the results show that an immersive VR setup provides a spatial perception that is mostly but not entirely comparable to that in a real environment. In both environments, when either of the geometrical and featural cues was presented alone, the participants chose the corner based on the spatial cues associated with the rewarded corner during the training trials. Also, the participants could remember the shape and the color of the featural cues. On the other hand, when the preference between geometrical and featural cue was tested, the participants chose geometrical cues in the real environment, while they chose featural cues in the immersive VR environment. The outcomes suggest the difference in spatial perception might be a limitation of immersive VR environments. As the narrowed field of view does not degrade distance estimations in a real environment setup, the less salient geometry perception should have been caused by other factors. One possible explanation would be visual fidelity, namely the detailed texture presented on the walls in the real environment, which was not reproduced in the immersive VR setup. Another possibility would be the optical design of the headset. The virtual distance of the screen to present virtual environments is fixed at approximately 4.5 feet [2], yet one has to estimate the distance of an object in the virtual environment using conversion of the eyes. The optics of the headset also causes lateral chromatic aberrations that degrade image quality (namely contrast) at the peripheral vision. Furthermore, the pixel density of the display panel equipped on the head mounted display should be improved to avoid screen-door effect [3]. Aside from the optical design, the mass of the headset and maneuvering the wheelchair might have not been natural to some participants, resulting in different performance in the immersive VR setup used in this thesis. Nevertheless, an exposure to the VR setup for a long duration may allow human adults to overcome these shortcomings; human adults might be able to use geometrical component of the environment after practice, similar to how they would do in a real environment.

As for the difference in the use of geometrical or featural cues among young and older adults in an immersive VR setup (Chapter 3, [4]), both age groups showed a strong reliance upon featural cues; this was confirmed by object recognition trials that featural cues were encoded. The older adults exhibited a greater frequency of navigation pattern which could not be explained by the spatial cues presented. In other words, the older adults showed more difficulty in adjusting to environmental changes. However, it must be noted that the geometry of the environment might be less salient than it would be in a real environment, as discussed in Chapter 2. Thus, the strong reliance upon featural cues might not be true when the experiment is conducted in a real environment; in other words, young and older adults may use geometry and exhibit difference during navigation in a real-world. Another limitation of the study presented in Chapter 3 is that the participants' vision was not examined by an optometrist prior to the study. Although none of the older adults made error during object recognition trial, the exhibited less consistent navigation strategy among them could be due to a declined vision, namely the visual acuity and contrast sensitivity. It is possible that vision decline in older adult participants could have resulted in less reliance on the landmarks during their navigation. Investigating the correlation between their vision and navigation strategies may reveal whether vision would affect navigation strategy and its consistency. Moreover, individual analysis would provide deeper insights of navigation strategy. For example, it would be possible to compare consistency in navigation strategy for each individual between young and older adults, which might identify a group of the older adults that exhibits inconsistent navigation strategies across different testing conditions. The larger variations of age in the older group might account for not being able to detect a plausible difference between young and older adults. Ideally, the standard deviations of the age should have been matched between the two age groups.

As for the serious game presented in Chapter 4 to test the integration of geometrical cues, both young and older adults exhibited similar frequencies of each type of mistake; no significant difference was found between the two age groups within first 5 sessions in efficiency to solve the task. Over the training sessions, that was done only for older adults, they showed a reduced frequency of mistakes; this indicate older adults learned to use the geometrical cues within the environment. However, these results do not guarantee that older adults always learn to integrate geometry under all circumstances. Different combinations of environmental design, training-testing trials and outcome measures may contrast difference between the two age groups better. Although we did not find any significant difference between the genders in our studies, there are some studies that claim different results among the genders of the same age [5, 6]. In terms of usability, all participants including the older adults found the iPad platform intuitive and easy to interact with. This suggests such a serious game can be distributed to reach a greater number of participants to allow analysis in a larger population in a future study.

Overall, we showed the feasibility of both immersive VR and non-immersive virtual environment setups for investigating spatial cognition studies for older adult population. The results of the experiments in this thesis suggest that the immersive VR setup requires a cautious design and interpretation to draw conclusion on spatial performance in a real environment. In the study presented in Chapter 3, the immersive environments caused motion/simulator sickness (cyber sickness) in about 25% of the study subjects (25 of 101). Thus, for those who could not complete the experiment in an immersive mode due to simulator sickness, we used a non-immersive mode of the experiment. Of the 25 study subjects, 11 could not complete the experiment. The cyber sickness was not observed in any of the participants in another study with the same input device (VRN Chair) (Chapter 2), and neither in the 2D experiment (Chapter 4). The reason for the difference frequency of cyber sickness occurrence among the two studies presented in Chapters 2 and 3 using the same input device should be investigated in a future study.

The findings of this thesis provide an insight about the effect of aging in spatial knowledge in the use of geometrical and featural cues. Also, feasibility of a virtual environment design as a brain exercise serious game was demonstrated. While further research is necessary to investigate how human aging impacts navigation, the results are encouraging as we showed older adults still learn to effectively use geometrical cues to find a location within the environment as presented in Chapter 4. Brain imaging such as magnetic resonance imaging

(MRI) can be used to investigate a correlation between hippocampal volumes and the learning of the geometrical cues usage among older adults [7, 8].

5-2. Suggestion for future work

5-2 (a) Investigating aging effect in the use of geometry and feature in an immersive VR environment.

In the study presented in Chapter 3, the findings show a strong preference for featural cues when navigating towards a target in an immersive VR environment. However, a comparison between young and older adults on when geometrical cues are preferred remains unclear. The analysis of the traversed trajectories in that study suggests that the participants were able to reproduce the learned route at the beginning of testing trials towards the first landmark, which was invisible in the start location. However, when all the landmarks were removed, more than half of the participants could not find the target door at the end of the trial.

Previous studies showed that geometrical cues are preferred in a small environment [9-12]. Thus, the effect of the environment's size on the preference between geometrical and featural cues should be investigated. Do young and older adults encode strongly and prefer geometrical cues in an environment smaller than the one employed in the study presented in Chapter 3?

To address this research question, we suggest to expose young and older adults to an immersive VR environment with five intersections, one turn, and three distinct landmarks towards the target location. Preference of geometrical or featural cue should be investigated, and compared between young and older adults. Another task could be to locate objects on a map to provide finer granularity for assessment of spatial representation of landmarks. The accuracy of their localization of the landmarks should be assessed as a part of participants performance. Investigating the usage of the properties of featural cues would be also interesting. Similar to the manipulation applied in the study presented in Chapter 2, manipulating the shape, the colour, or even the angle of the featural cues can reveal how the featural cues are used during navigation. Those tasks can provide insight into the usage of an immersive VR environment in investigating aging effect during a navigational task.

5-2 (b) Investigating aging effect in the use of geometry and feature in 2D non-immersive virtual environment.

In the study presented in Chapter 4, although learning to use geometrical cues among young and older adults was investigated, the preference between geometrical and featural cues remains unclear in a 2D non-immersive virtual environment. A previous study shows the feasibility of using such environment to study preference between geometrical and featural cues [13].

With a 2D non-immersive virtual environment, dimension of the screen is determined by a device used (i.e., iPad), which cannot be changed regardless of the size of virtual environment. Thus, it is of interest whether the preference of geometrical or featural cue changes when the dimension of the virtual environment changes. Also, it is of interest whether the pattern of the change differs between young and older adults. In other words, do young and older adults show the same pattern of the preference of geometrical or featural cue, when the size of 2D non-immersive environment changes?

Two sets of environments could be designed to address the above research question: one is a replica of the hallway environment presented in Chapter 3, and another is a smaller environment, which is a matrix of hallways with five intersections, one turn, and three distinct landmarks towards the target location. Those environments could be presented on iPad, and young and older adults could be recruited. Similar to the previous section, preference of geometrical or featural cues should be investigated, and compared between young and older adults. The task to locate objects in a map will be added as well. Those tasks would provide insight to design 2D non-immersive virtual environment such that what aspect of spatial cognition changes while aging.

5-2 (c) Learning geometry in an immersive VR environment.

The results of the study presented in Chapter 4 show that young and older adults learned to use geometrical cues similarly when a 2D non-immersive virtual environment was used. However, the results of another study, which employed non-intuitive input device, show age difference during a learning task of a maze layout [10]. Another difference between the studies is the design of the environment. At the beginning of a trial, the target location was visible in a hexagonal room employed in the study presented in Chapter 4, whereas the target location was invisible in a maze employed in the other study. Thus, the source of the reported age difference could be due to either the input device or the environment’s design, namely whether the target is visible in a start location.

To investigate which of the factors correlates better with age difference, young and older adults should be tested in a maze environment, in which the target is invisible in a start location, using an immersive VR setup. The question is whether young and older adults learn a maze similarly in the 3D immersive VR environment with similar results as presented in [14]. A far transfer can also contrast the two age groups. Employing an independent task can reveal whether they can transfer their knowledge of using geometry under another environment.

A hallway presented in Chapter 3 as the No Landmark condition (i.e., a path with 7 intersections, 4 turns, and no landmark) in an immersive VR environment can address the above research question. The number of blocks of training trials until young and older adults learn the path with no deviation from the trained route should be investigated and compared. The task would allow to examine the possibility of an immersive VR environment of training geometry usage. The task would possibly examine the difference between young and older adults in their learning process of geometry usage as well.

5-2 (d) Avoiding cyber sickness in VR experiments.

In the study presented in Chapter 4, when the environment was a 2D hexagonal room, no participants suffered from cyber sickness. By contrast, in the study presented in Chapter 3, when the environment was a matrix of hallways in 3D immersive mode, about 25 percent of the participants reported cyber sickness using the immersive VR setup. It suggests that the immersive VR setup might have caused cyber sickness. However, no participant reported cyber sickness in the study presented in Chapter 2 despite the input device

(VRNChair [15]) being identical to that in the study presented in Chapter 3. Thus, the design of the VR environment might be the reason for cyber sickness in the latter study.

Three major factors differed between the studies presented in Chapters 2 and 3. Firstly, a greater number of turns was required to find the target during the latter study (Chapter 3); the former required only one turn, whereas the latter required four turns. Secondly, the former employed virtual room of either 6.87 × 3.3 or 3.3 × 3.3 virtual unit (vu), whereas the latter employed environments of 27 × 32 vu with a width of 2 vu for each hallway. Lastly, the sensitivity of the input device (VRNChair) differed between the two studies. When the participants moved 1 meter physically, they were moved by 1 vu and 2 vu in the former and the latter studies, respectively. This difference was made on purpose so that the bigger VR environment experiment could also be run in a limited, but reasonably large physical space. For a 1:1 ratio of physical to virtual movement, we would have needed a 27 × 32 meter (864 m^2) physical environment free of any obstacle. Taken together, one question to be addressed is whether frequent turns in a narrower environment and higher ratio of physical to virtual unit movement induce cyber sickness.

To answer that, a physical environment of 5 × 5 meter (25 m^2) should be secured; this space is feasible compared to 27 × 32 meter (864 m^2). Four environments with a dimension of 5 × 5 vu each should be designed. To manipulate the number of turns, one path would be walking along the walls with only one turn (see Fig. V- 1(a)), while the other path would be walking the same distance, but across the environment with many turns (see Fig. V- 1(b)). For each path, two environments would be designed to manipulate the width of the environment; two environments should only have surrounding walls (Figures V- 1(a) and (b)), while other two environments should have extra walls along the predetermined path (Figures V- 1(c) and (d)) to limit the width.

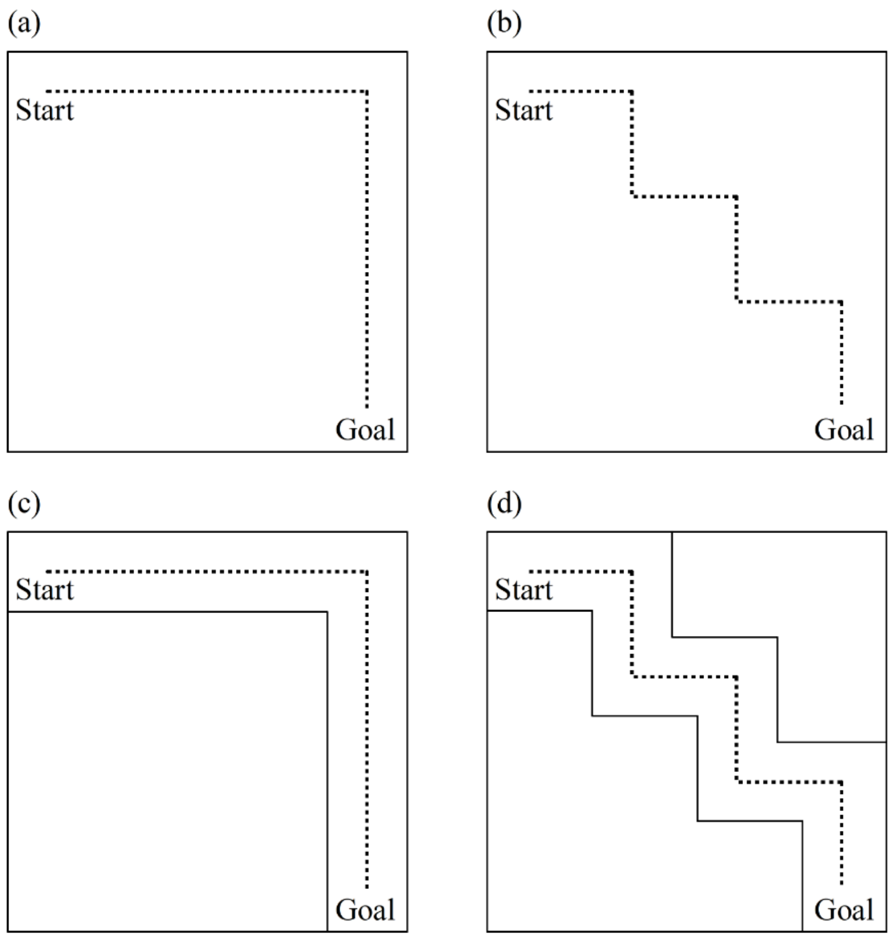

Figure V- 1. Schematics of suggested environments to investigate the cause of cyber sickness. The solid lines indicate walls, and the dotted lines indicate the path that participants would be asked to follow.

Comparison of the performance in the VR environments in Figures V- 1(a) and 1(b) determines whether the increased number of turns increases the cyber sickness as both environments have the same width (field of view). Comparison of the environments a and c of the Fig. V- 1 can investigate the effect of width on the induced cybersickness. Furthermore, comparing environments c and d of the Fig. V- 1 can investigate the added effect of turns in a narrow width on the induced cyber sickness.

For each of the four environments, two different sensitivities should be employed: 1 vu and 2 vu motion for 1 meter of physical movement to investigate its effect on the induced cyber sickness The task would be following the dashed lines indicated in Fig. V- 1, and the degree of cyber sickness should be measured and compared using Simulator Sickness Questionnaire [16]. The comparison would provide a better understanding of the effect of environment size and sensitivity on cyber sickness in an immersive VR setup.

The above suggested study should be run on at least 30 healthy young adults on different days: each experiment has to be run on a separate day, and the order of experiments should be randomized among the study participants.

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Appendix A. Participants' informed consent form

RESEARCH PARTICIPANT INFORMATION AND CONSENT FORM

Title of Study: "Investigating Human's spatiotemporal Perception using haptic computer games"

Protocol number: "___5____"

Principal Investigator: "Dr. Zahra Moussavi, Electrical & Computer Engineering, University of Manitoba, 204-474-7023 "

Sponsor: *"NSERC"*

You are being asked to participate in a Clinical Trial (a human research study). Please take your time to review this consent form and discuss any questions you may have with the study staff. You may take your time to make your decision about participating in this clinical trial and you may discuss it with your regular doctor, friends and family before you make your decision. This consent form may contain words that you do not understand. Please ask the study doctor or study staff to explain any words or information that you do not clearly understand.

This study is financially supported by the University of Manitoba and NSERC.

Purpose of Study

The objective is to test the sense of time/speed and orientation using interactive computer games. A total of 400 participants will participate in this study.

The results of this study help in better understanding of human brain development and cognitive learning and also to detect the early signs of Alzheimer disease.

Study procedures

If you take part in this study, you will be instructed to play two virtual reality games. They are designed to assess human brain temporal and spatial processing abilities. You are not required to know any computer knowledge to play the games; they are fun and engaging. The games are to navigate inside a virtual building to reach a predefined destination. Once you have played the games, if interested, you may ask us to describe the data analysis procedure. To play the orientation game, you will be asked to wear a goggle and sit in a manual wheelchair, which you will navigate it through a virtual building. Once you wear the goggle you will be totally immersed in the virtual environment and feel yourself present in that environment. The experimenter will walk beside your wheelchair to ensure you do not hit any obstacle in the real environment.

You may also take one or two cognitive tests to assess your short-term memory. There is no other requirement. If you are 50+ year old, we would encourage you to participate in our study for a few more times, each 6 months apart.

If at any time while playing the games, you decide to stop participating in this study, you can simply leave the game and request the study staff to help you out of the on-going experiment.

If interested, the results of this study will be provided to you upon your request.

Risks and Discomforts

There is no side effect as a result participating in this study. However, if you feel discomfort by any mean during your participation in this experiment, you can ask study staff to take you off the study. Your condition may not worsen while participating in this study.

Confidentiality

Information gathered in this research study may be published or presented in public forums; however, your name and other identifying information will not be used or revealed. Medical records that contain your identity will be treated as confidential in accordance with the Personal Health Information Act of Manitoba. Despite the efforts to keep your personal information confidential, absolute confidentiality cannot be guaranteed. Your personal information may be disclosed if required by law.

All study documents related to you will bear only your assigned code and /or initials. Your data acquired during the games will be recorded and stored in computer files with your code. These data will be analyzed for the main purpose of study which is to investigate the human brain development and motor learning that lead to skilled human movement in terms of temporal and spatial accuracy. Students and researchers who will analyze your data will not have access to your identification and only know the files by their codes.

The University of Manitoba Health Research Ethics Board may review research-related records for quality assurance purposes. All records will be kept in a locked secure area and only those persons identified will have access to these records. If any of your medical/research records, need to be copied to any of the above, your name and all identifying information will be removed. No information revealing any personal information such as your name, address or telephone number will leave the University of Manitoba.

Voluntary Participation/Withdrawal from the Study

Your decision to take part in this study is voluntary. You may refuse to participate or you may withdraw from the study at any time. You will not lose any benefits or care to which you are entitled upon the refusal to participate in or withdraw from the study.

We will tell you about any new information that may affect your health, welfare, or willingness to stay in this study.

Questions

You are free to ask any questions that you may have about your treatment and your rights as a research participant. If any questions come up during or after the study, contact the study doctor and the study staff: Dr. Zahra Moussavi at 204-474-7023.

For questions about your rights as a research participant, you may contact The University of Manitoba Biomedical Research Ethics Board at (204) 789-3389. Do not sign this consent form unless you have had a chance to ask questions and have received satisfactory answers to all of your questions.

Statement of Consent

I have read this consent form. I have had the opportunity to discuss this research study with Dr. Zahra Moussavi and or his/her study staff. I have had my questions answered by them in language I understand. The risks and benefits have been explained to me. I believe that I have not been unduly influenced by any study team member to participate in the research study by any statement or implied statements. Any relationship (such as employee, student or family member) I may have with the study team has not affected my decision to participate. I understand that I will be given a copy of this consent form after signing it. I understand that my participation in this clinical trial is voluntary and that I may choose to withdraw at any time. I freely agree to participate in this research study.

I understand that information regarding my personal identity will be kept confidential, but that confidentiality is not guaranteed.

By signing this consent form, I have not waived any of the legal rights that I have as a participant in a research study.

I agree to being contacted in relation to this study. **Yes** □ **No** □

Participant signature__________________________ Date ____________________

(day/month/year)

Participant printed name: _____________________________

__________________________ For Children Participants only

____

Parent/legal guardian's signature (if applicable): ____________________

Date _________________

Parent/legal guardian's printed name (if applicable): ___________________________

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I, the undersigned, have fully explained the relevant details of this research study to the participant named above and believe that the participant has understood and has knowingly given their consent

Printed Name: _________________________ Date ____________________

(day/month/year)

Signature: _____________________________

Role in the study: __________________________