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Improving distance perception in virtual reality

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ABSTRACT

Virtual reality (VR) is a useful tool for researchers and instructors alike. VR allows for the development of scenarios which would be either too dangerous or too costly to create in the real world such as distracting a driver in a virtual vehicle. Unfortunately, distances tend to be underperceived within VR, and consequently, the validity of any training or research performed within a virtual environment could be called into question. In an effort to account for underperception, this project sought to establish an interaction task as both environment and task neutral that could be applied to the beginning of any virtual training or research task to correct underperception.

Experiment 1 found that improvements in distance perception from an interaction task could likely be transferred from one environment to another but that there might be issues with removing distance cues from later environments.

Experiment 2 found that the presence of walls drove the effect in experiment 1. Results also indicated that interacting with an environment likely encourages participants to rely on the given distance cues and therefore cause a decrement in performance when these cues are later removed.

Experiment 3 gave evidence for the presence of both environment rescaling and behavioral recalibration as a result of interacting with a virtual environment. It also gave support for a more general rescaling that can improve performance at distances beyond those used for interaction.

CHAPTER 1: INTRODUCTION

General Introduction

Virtual reality (VR) is an important tool for our modern world because it allows researchers to create environments that are either impossible or impractical within the real world as well as situations that would be too dangerous to test with other methods. For example, human factors researchers use virtual reality to test distracted drivers on models of actual roads because, unlike the real world, there are no consequences for a 50mph collision. Heads up displays can also be modeled in VR to determine their efficacy before building an actual prototype, saving firms thousands of dollars and weeks of development time. Psychological studies have also employed VR in order to allow the creation of non-existent environments where all visual cues can be controlled and manipulated. Instead of building false walls within a lab, VR can facilitate rooms or other environments of any shape and size and in any configuration with the only limit being the individual researcher's artistic and programming abilities. VR is not just a research tool, but also widely used in training scenarios. Many pilots familiarize themselves with, and learn to fly, their respective craft in a virtual environment (VE) before being allowed into an actual cockpit where it could be potentially fatal to allow an inexperienced pilot to handle the controls.

Although VR is intended to be an analog for the real world, it does not always accurately represent our experiences in the natural world. One such difference is a tendency for viewers to underestimate egocentric distances within VR. Studies have shown that people are accurate when attempting to determine distance to a target in the real world (Loomis & Knapp, 2003; Thompson, Eillemsen, Gooch, Creem-Regehr, Loomis & Beall, 2004) but they tend to underestimate distances to virtual targets, implying that participants are underperceiving distance in VR. A review by Waller & Richardson (2008) found that participants, on average, will only perceive distances to be 71% of actual while in VR.

Measuring Perceived Distance

Directly measuring distance perception is not possible, however several different behavioral methods have been employed to infer the effect of certain manipulations on perception. Direct blind walking is a method where participants look at a target before being blindfolded and then asked to walk in a straight line to the target. The distance walked is interpreted as the perceived distance (Waller & Richardson, 2008; Knapp & Loomis, 2004; Richardson & Waller, 2005; Kelly, Hammel, Siegel & Sjolund, 2014; Kelly, Donaldson, Sjolund, & Frieburg, 2013). Unlike direct blind walking, indirect tasks ask the blindfolded participant to walk in another direction before turning to face the target and either walking toward (triangulated walking) or pointing at (triangulated pointing) the target. The intersection of the triangulated vector and a line connecting origin and the target is interpreted as perceived distance (Thompson et al. 2004). Indirect tasks have been employed to prevent participants from easily planning behavior during the viewing phase (e.g., planning to walk a certain number of steps when performing a blind walking response). Triangulated provide accurate responses similar to those of blind walking (Fukushima, Loomis, & Da Silva, 1997). Blind throwing tasks have also been used when contrast from a walking response was desired. A blind throwing task simply asks the participant to, while blindfolded, throw a beanbag or ball toward the previously viewed target. The impact point of the object is interpreted as perceived distance (Wu, He, & Ooi, 2007). In addition to the motoric responses mentioned above, verbal responses have also been used to estimate distance perception.

One common verbal response asks participants to stand still and give a verbal report of the distance from their position to the target (Knapp & Loomis, 2004; Kunz, Wouters, Smith, Thompson & Creem-Regehr, 2009). The reported distance is assumed to be the participant's perception of distance. Another verbal method asks participants to stand still while looking at a target object before giving a verbal estimation the target's size (Kelly, Donaldson, Sjolund & Freiberg, 2013). Estimations of target size are used to estimate perceived distance because the size-distance invariance hypothesis (Sedgwick, 1986; Kelly, Donaldson, Sjolund, & Freiberg, 2013) states that an object's perceived size (S') is directly related to perceived object distance (D') and angular size (α):

$$S' = 2D' \, x \, tan(\alpha/2)$$

When distance is accurately perceived, objects should appear to be of constant size irrespective of physical distance. If two objects have the same angular size, the object which appears farther away will also look physically larger. Thus, the verbal report of size indicated by the participant is interpreted as a measure of perceived distance.

It is important to note that the methods listed above all measure *egocentric* distance perception. Egocentric distance is the distance between the observer and another target, for example, the distance you perceive from your eyes to this paper. By contrast, *exocentric* distance is the distance between two targets unrelated to the observer. This paper will only consider egocentric distance perception as the majority of literature regarding distance perception within VR focuses on egocentric perception and manipulations that improve egocentric perception may not necessarily improve exocentric perception.

Perceived Distance In The Real World

Performance on distance perception tasks in the real world tends to be very accurate for egocentric distances up to 20 meters (Loomis & Knapp, 2003), and in a study by Waller and Richardson (2008), participants showed near perfect direct blind walking responses in the real world. Loomis and Knapp (2003) review studies which show that not only are real world distances perceived accurately, but verbal and motoric responses are highly correlated. Even though motoric and verbal responses are highly correlated, a study by Kelly, Loomis and Beall (2004) has shown that some verbal responses tend to show a degree of underperception in the real world which is not present with motoric responses such as in Waller and Richardson (2008) or Thompson et al. (2004).

Perceived Distance In VR

To examine the accuracy of perceived distance in VR, Witmer and Sadowski (1998) modeled a monochrome 3D version of a hallway and placed a cone at varying distances from the participant. After a viewing time, participants were blindfolded and then attempted to walk to where the cone had been. Participants in the virtual environments showed more underperception and greater variability than participants in a real world condition. Several possible explanations for underperception were offered, such as differences in lighting, poor graphical quality, and limited field of view in the Head Mounted Display (HMD).

Underperception of distances in VR is a serious concern for those that use these systems, both for research and training. As explained earlier, virtual reality allows researchers to explore many scenarios which they would not normally have access to; however, validity could be called in question for any measures that rely on distance. For example, studies which look at distracted drivers often measure how far in advance brakes are applied (Godley, Triggs, & Fildes 2002), but if distance is underperceived, the results may be biased and difficult to interpret. Underperception of distance could alter when the participant believes he or she needs to brake, but also the perceived speed of a vehicle which would, in turn, affect the stopping distance as well.

Training performed with underperceiving participants also raises concern. If pilots were solely trained in simulators, the skills learned with improper distance perception could cause a pilot to take action too late and cause a crash.

Correcting Underperception

There are two main approaches to solving the problem of underperception of distance, bottom-up and top-down. The bottom-up approach attempts to identify problems with the stimuli in a virtual environment and then correct those problems to provide a perceptual experience closer to the intended. As mentioned previously, graphical differences between the real world and a virtual display could affect the way that distances are perceived. Thompson et al. (2004) examined the effect of graphical quality by comparing distance perception in three virtual environments that differed only in fidelity and compared them with performance in the actual space the VEs were modeled after. The three graphical levels consisted of a photo-realistic rendering, a low-resolution rendering typical of virtual environment used in research, and a wireframe model of the same environment. All virtual environments were displayed on the same hardware possessed the same field of view (FOV). Thompson and colleagues (2004) found that participants performed near veridical in the real-world control, but underperceived in all three virtual environments. Furthermore, no significant different in performance was found between the virtual environments. In a more recent paper, Kunz et al. (2008) reported that while environment detail has no effect on distance judgments, verbal reports are more accurate in high quality virtual environments. The authors suggest several possibilities as to why these responses show different effects based on multiple representations, task-specific representations, or differing impact on judgment. More importantly for this thesis, the authors caution against assuming that all responses behave similarly in VR. Including additional response types will provide more generalizable results than a single response measure.

Behind visual fidelity, field of view is perhaps the next most readily visible difference between real and virtual environments. Almost all HMDs are incapable of rendering images to the full 180 degree horizontal range that our eyes can see, with common HMD systems ranging from 40 to 100 degrees. Some have suggested that the reduced field of view in a virtual environment could be a partial cause of underperception. Knapp and Loomis (2004) conducted a study in which participants performed both blind walking and verbal judgments of perceived distance in the real world while their vision was unobstructed, or while wearing a simulated HMD designed to reduce the field of view to that of an average VR display (58 degrees). Results showed that participants performed the same regardless of whether or not their field of view was restricted. In sum, the bottom-up approach has thus far been unable to identify the missing or incorrect visual cues that lead to underperception of distance in VR.

Whereas the bottom-up approach focuses on altering the stimuli to produce perceptual experiences that are more in line with real world experiences, top-down methods aim to change the way that the participants perceive and/or respond to the environment with methods other than altering the stimuli, such as training or experience. One such method has employed a training task where participants walked to a virtual object with feedback, allowing the participant to modify the association between perceived distance and a walking response. In a study by Richardson and Waller (2005) participants walked to a previously viewed post while blindfolded, showing underperception as in past studies. After this blind walking pre-test, participants looked at a computer screen on which they were shown how far they had walked and were also given a written description of the distance walked compared to the actual target distance. After this training task, blind walking accuracy improved from 58% of actual distance before training to 102% of actual distance after training. Feedback not only improved distance judgment accuracy but a retention task one week later showed that performance was still significantly more accurate than the pre-test. However, it is unclear from those results whether training actually changed perceived distance or whether training recalibrated the walking response.

In our own lab, we have further pursued the nature of improvement in VR using an interaction task in which feedback about actual object distance is provided. The first experiment reported by Kelly, Hammel, Siegel and Sjolund (2014) examined the benefit of multiple interaction blocks on blind walking distance judgments. Participants first performed a blind walking task in VR to determine their baseline underperception. After this pre-test, participants alternated between blocks of interaction and test blocks for a total of 1 pre-test, 3 interactions, and 3 post-tests. Each interaction block consisted of five trials in which a blue target post was visible along with numerous thin grey posts scattered around the environment to provide additional optic flow. Participants walked from the starting point to the target while the environment remained visible. Once the participant reached the target, the screens went blank and the participant stepped backwards to the starting point to begin another trial.

Results from this study showed improvement in blind walking accuracy after each interaction block, but the majority of improvement took place after only the first interaction block (five trials). Improvement diminished after each interaction block and the fourth interaction block did not show significant improvement over the third. Furthermore, distance perception never reached veridical. Although interaction with a virtual environment can improve the accuracy of behavioral responses, the improvement is subject to rather strong diminishing returns that may make repeated interaction trials not worth the time and effort (Kelly et al. 2014).

The second study reported by Kelly et al. (2014) examined how altering the distances experienced in the interaction would affect the improvement in blind walking judgments. Participants were given a pre-test, interaction, and post-test, similar to the first study. The main difference in the interaction block was that two conditions were created by using different distances for the interaction trials. The near condition had participants only walk to close distances (1m and 2m) during the interaction trials while the far condition had participants only walk to far distances (4m and 5m). Pre- and post-tests evaluated perceived distance for distances 1-5 m. Results showed that interaction with short distances in the near condition improved blind walking accuracy at the near test distances only. However, interaction with longer distances in the far condition improved blind walking accuracy at all test distances. These results suggest that, in order to make an interaction task useful, participants must explore the entire space that will be used during the study or training exercise. This experiment is not diagnostic as to whether improvement is the result of recalibrating walking behavior or rescaling of perception because it is possible that rescaling only takes place at distances experienced during the interaction.

The studies mentioned so far have demonstrated that walking interaction leads to improved blind-walking distance judgments. There are multiple hypotheses that can potentially explain these results, including the recalibration hypothesis and the rescaling hypothesis. According to the recalibration hypothesis, feedback during walking interaction leads to adjustments in the blind walking response, such that participants walk farther after interaction. Importantly, the recalibration hypothesis only posits changes to the response, but not perceived distance. This means that recalibration is specific to the trained perception-response pair, and therefore walking recalibration should not affect other non-walking judgments, such as verbal reports, blind throwing, or size judgments. According to the rescaling hypothesis, interaction with an environment modifies the perceived size of the environment as a whole, also modifying perceptions of distance and size as a result. Because the rescaling hypothesis posits changes to perception of the environment, all tasks that rely on distance perception should be affected (and consequently improved). Unfortunately, the studies described so far are incapable of differentiating between recalibration of action and rescaling of perceived space, because the same walking action was used during both interaction and distance judgment trials.

In order to evaluate the recalibration and rescaling hypotheses, Kelly, Donaldson, Sjolund, and Freiberg (2013) performed a study in which participants performed a verbal size judgment task in addition to a walking task and a motor interaction. Size judgments were converted into size-based distance following the size-distance invariance hypothesis. Results of the size-based distance showed that participants did underperceive distance similar to the walking task. The size-based distance judgments also showed improved accuracy after interaction. The verbal size-judgment task used in this study showed a smaller improvement than the walking task and had much more variability due to individual differences. However, the similar pattern of initial underperception and subsequent improvement in the verbal size estimation task and the walking task still suggests that the interaction task is not just recalibrating the link between visual perception and walking behavior, rather interacting with the virtual environment likely rescales the perceived environment as a whole.

Previous studies, in our lab and others, have shown promise for correcting underperceived distance within VR through interaction. The proposed series of experiments attempt to develop a short, universal interaction task that can be performed before every VR study or training session to correct a large portion of underperception. In order to be universal, the task will first need to improve distance perception in a wide range of possible virtual environments. The improvement in the interaction environment should also carry over to any other virtual environment the researcher/instructor has designed for their task. These topics are considered in Experiments 1 and 2. In addition, the interaction should improve distance perception among a range of tasks. As mentioned earlier, recalibration of one specific response (e.g., walking) will improve distance judgments by altering the recalibrated response, but a universal task should rescale the perceived environment, allowing for correct distance perception when walking, throwing, and learning to land a virtual jet. This topic is considered in Experiment 3.

CHAPTER 2: EXPERIMENT 1

Introduction

Past studies have only examined the effect of interaction within a singular virtual environment, with the entire experiment (pre-test, interaction, and post-test) taking place in the same environment (e.g., a grassy field). This study was conducted to test whether interaction performed in one virtual environment will benefit distance judgments in a subsequent, novel virtual environment, making the interaction task universal with respect to environment. Participants performed a pre-test, interaction, and post-test in one environment and then performed another pre-test, interaction, and post-test in the same environment (stay condition) or in a novel environment (switch condition). As the first post-test and second pre-test were performed without an intervening interaction, any difference between those tests in the switch and stay conditions will represent the amount of recalibration that transferred across environments. This particular interaction task was chosen because it has been used before in the literature and was used by our lab for the 2014 Kelly et. al study. By using the same interaction task, we are able to consider the results from all of these studies together.

In order to capitalize on data already being collected, a second research question was added to this study. Because virtual environments are not yet ubiquitous in our society, it is possible that the novel nature of VR could be contributing to underperception of distance. Studies have also shown that video game play can improve ability on a number of different spatial cognitive processes such as spatial perception, attention, memory and visuomotor coordination (Spence & Feng, 2010). While video games have not been used to examine the distance underperception phenomenon, it is worth considering video games as a potential training method. The wide range of spatial cognition that can be trained with video games makes it possible that distance perception is yet another trainable aspect.

Though video games can be used to train spatial skills, Sims & Mayer (2002) have shown evidence that transfer of video game training is limited to tasks which share distinct features with the game. For example, Tetris skill was shown to transfer to mental rotation of shapes, but not to other spatial skills like paper folding and letter rotation. It is also possible that distance perception in VR is not similar enough to video game training and no effect will be found.

In light of the video game training literature, and in order to rule out video game play as a potential confound, participants were asked about their video game habits in order to determine if prior experience with a virtual environment affects the degree of underperception, rate of improvement due to interaction, or transfer of interaction-based improvement. Because the previous studies mention sex and other spatial abilities as reasons people choose video games as a hobby, additional measures were collected to control for these factors.

Method

Participants

65 undergraduate students from Iowa State University participated for course credit. One additional student was removed from analyses because over half of the initial distance judgments were less than 10% of actual. Participants were randomly assigned to one the four conditions and gender was approximately balanced across condition.

Stimuli and Design

The virtual environment was displayed on a HMD (nVisor SX111, NVIS, Reston, VA). Stereoscopic images were presented at 1280 x 1024 resolution with 102° horizontal x 64° vertical field-of-view. Images were refreshed at a rate of 60 Hz and reproduced head movement and orientation of the participants as they navigated the virtual environment. Vizard software (WorldViz, Santa Barbara, CA) was used to render graphics on a desktop computer with Intel Core2 Quad processors and Nvidia GeForce GTX 285 graphics card.

The grass environment consisted of an endless, flat plane with a grass floor texture (figure 1). The room environment consisted of a rectangular room with a tile floor, brick walls, and an un-textured tan ceiling (figure 2). Both environments were illuminated from behind the participant's starting position.

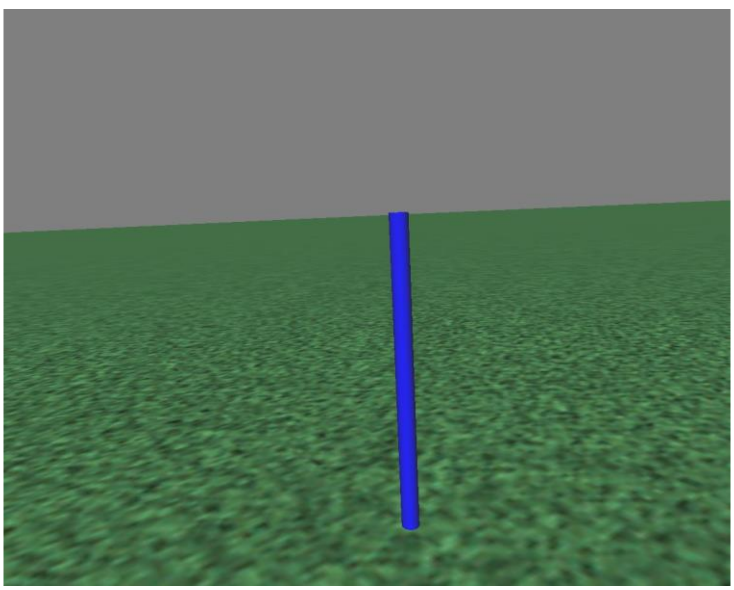

Figure 1. Grassy field environment.

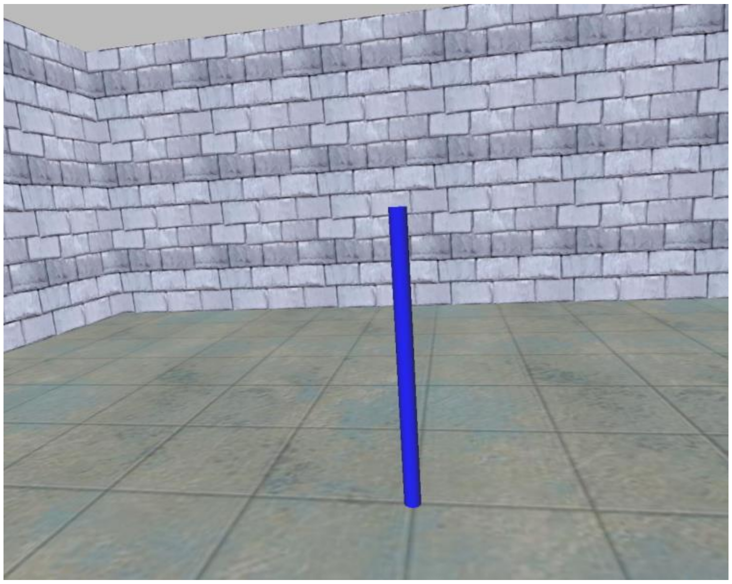

Figure 2. Room environment.

To assess video game play, a survey was collected asking participants how many hours of video games they played per week (See Appendix A). Participants also performed a mental rotation task (Vandenberg & Kuse, 1978) (See Appendix B) in order to isolate the effect of video game play on distance perception.

Participants were randomly assigned to one of four 2x2 factorial conditions. First, participants either performed the stay or switch condition of the study. Stay condition participants performed the entire study within the same environment while switch condition participants began the experiment in one environment before changing to the other halfway through. Second, participants either started on the grassy field or in the room. The four conditions will be referred to as stay-grass, stay-room, switch-grass (start in grass and switch to room), and switch-room (start in room and switch to grass).

The study consisted of two blocks, each of which had 15 pre-interaction distance judgments ("pre-test"), followed by 15 interaction trials, and then 15 post-interaction distance judgments ("post-test"). During the pre-test trials, participants were asked to stand still while looking at a blue target post with height scaled to participant eye level.

After 5 seconds, the entire screen turned grey and the participant walked, blind to the environment, to where they believed the post had been. Walking distance was recorded and participants walked backwards to the starting position with guidance from the experimenter. During the interaction trials, the environment was the same as pre-test except for the addition of 150 thin grey poles randomly scattered in the environment except in the space between the target and participant. Participants walked to the target post, and the environment disappeared once they arrived at the target. Finally, the post-test was identical to the pre-test. During pre-test, interaction, and post-test, participants walked to each of five pole distances between 1-5 m away. After the first block, the environment either changed or remained the same depending on condition and then the identical second block began.

After both blocks in the virtual environments were completed, participants performed a mental rotation task followed by the video game habits survey.

Results

Proportion of distance walked is shown in figures 3-6 as a function of target distance (1m, 2m, 3m, 4m, and 5m) and test (first pre-test, first post-test, second pre-test, and second post-test), with separate graphs for each of the starting environment/condition pairs (stay-grass, stay-room, switch-grass, switch-room. Participants in the stay condition showed improved distance perception after each block of interaction and no difference was found between the first post-test and the second pre-test. Participants in the switch condition showed improvement after each block of interaction similar to those in the stay condition. In addition, accuracy improved between the first post-test and second pre-test for participants who switched from the grassy field to the room (figure 5). However, participants who switched from the room to the grass plane showed a reduction in accuracy after the environment switch (figure 6). These conclusions were supported by the statistical analyses.

Proportion of actual distance walked was analyzed in a mixed-model ANOVA with between subject terms for first environment (grassy field and room) and condition (stay and switch), and within subject terms for target distance (1m, 2m, 3m, 4m, and 5m) and test (first pre-test, first post-test, second pre-test, and second post-test), see table 1. Due to the large number of potential effects, an alpha of .01 was selected for all statistical tests. Significant main effects of test $F(3,180) = 53.569$, $p < .001$, $\eta_p^2 = .472$, and distance $F(4,240) = 94.738$, $p < .001$, $\eta_p^2 = .612$ were qualified by a significant interaction between condition and first environment $F(1,60) = 9.569$, $p = .003$, $\eta_p^2 = .667$ as well as a significant interaction between test, first environment, distance and condition $F(12,720) = 2.249$, $p = .009$, $\eta_p^2 = .036$.

In light of the significant four way interaction, the stay and switch conditions were analyzed in separate mixed-model ANOVAs with a between subject term terms for first environment (grassy field and room) as well as within subject terms for target distance (1m, 2m, 3m, 4m, and 5m) and test (first pre-test, first post-test, second pre-test, and second post-test) see tables 2 and 3. For the stay condition, main effects of test $F(3,90) = 31.673$, $p < .001$, $\eta_p^2 = .514$, and distance $F(4,120) = 41.631$, $p < .001$, $\eta_p^2 = .501$ were significant and there were no significant interactions. For the switch condition, main effects of test $F(3,90) = 23.155$, $p < .001$, $\eta_p^2 = .436$, and distance $F(3,120) = 57.451$, $p < .001$, $\eta_p^2 = .657$, were significant with no significant interactions.

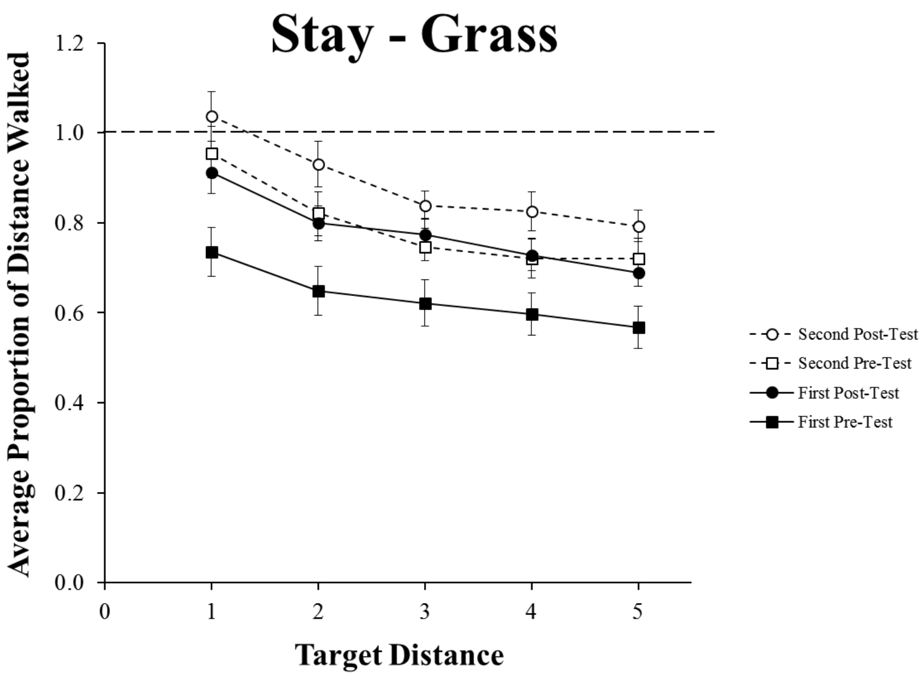

Figure 3. *Experiment 1 – Proportion of distance walked in the stay condition (grass) as a function of test and target distance. Error bars represent standard error.*

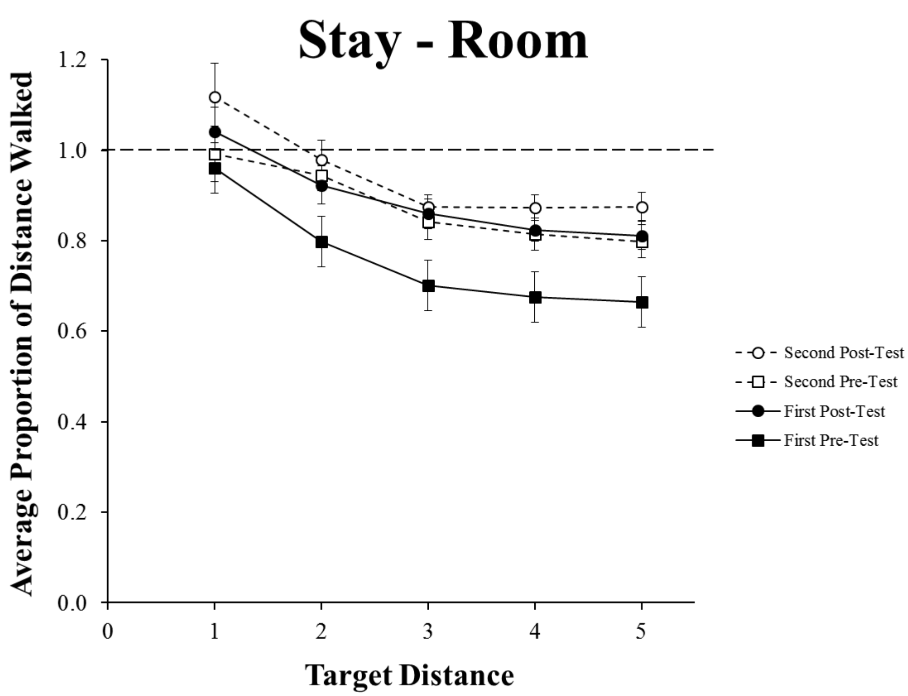

Figure 4. *Experiment 1 – Proportion of distance walked in the stay condition (room) as a function of test and target distance. Error bars represent standard error.*

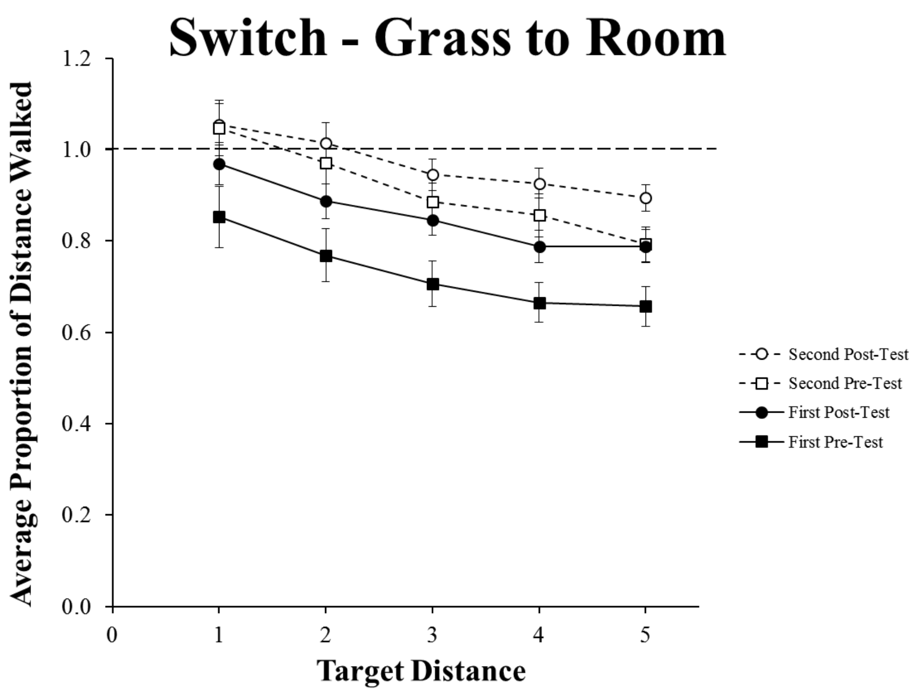

Figure 5. *Experiment 1 – Proportion of distance walked in the switch condition (grass to room) as a function of test and target distance. Error bars represent standard error.*

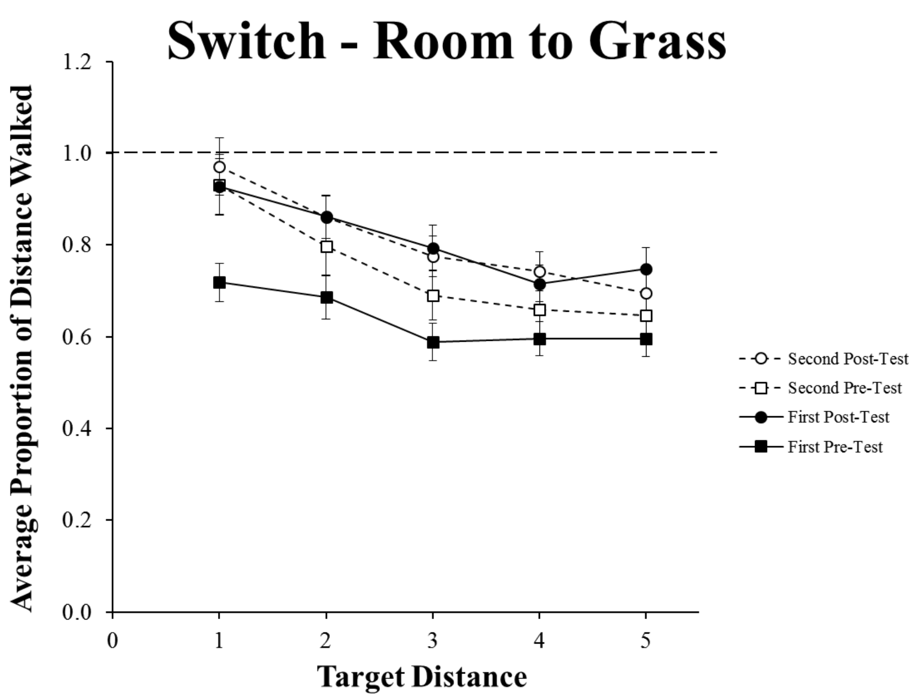

Figure 6. *Experiment 1 – Proportion of distance walked in the switch condition (room to grass) as a function of test and target distance. Error bars represent standard error.*

Because the motivation for this experiment was to evaluate changes in performance across tests, the data were further considered in terms of the proportion change from one test to the next. For example, the proportion change from the first pre-test to the first post-test should reflect the influence of the walking interaction, whereas the proportion change from the first post-test to the second pre-test should reflect the influence of the changed environment (in the switch condition only). Proportion change was analyzed in a mixed-model ANOVA with between subject terms for first environment (grassy field and room) and condition (stay and switch) as well as within subject terms for target distance (1m, 2m, 3m, 4m, and 5m) and test (first post-test, second pre-test, and second post-test) see table 4. Only a significant main effect of test $F(2,120) = 42.883$, $p < .001$, $\eta_p^2 = .417$ was present. Because there is no main effect or interaction regarding distance, figure 7 shows proportion change between test blocks for each environment/condition pair collapsed over distance.

Figure 7 shows a unique pattern of both positive and negative proportion change during the environment switch that was not expected. Based on this observation, and the significant main effect of first environment in the 4-way ANOVA as well as a marginally significant interaction of test, distance, and first environment in the 3-way ANOVA for the switch condition, one sample t-tests were run on the proportion change in distance walked between the first post-test and second pre-test for each of the four condition/first environment pairings. Only the proportion change for switch condition starting on the field $t(16) = 2.85$, $p = .012$, and for the switch condition starting in the room $t(16) = -3.57$, $p = .002$, were significant.

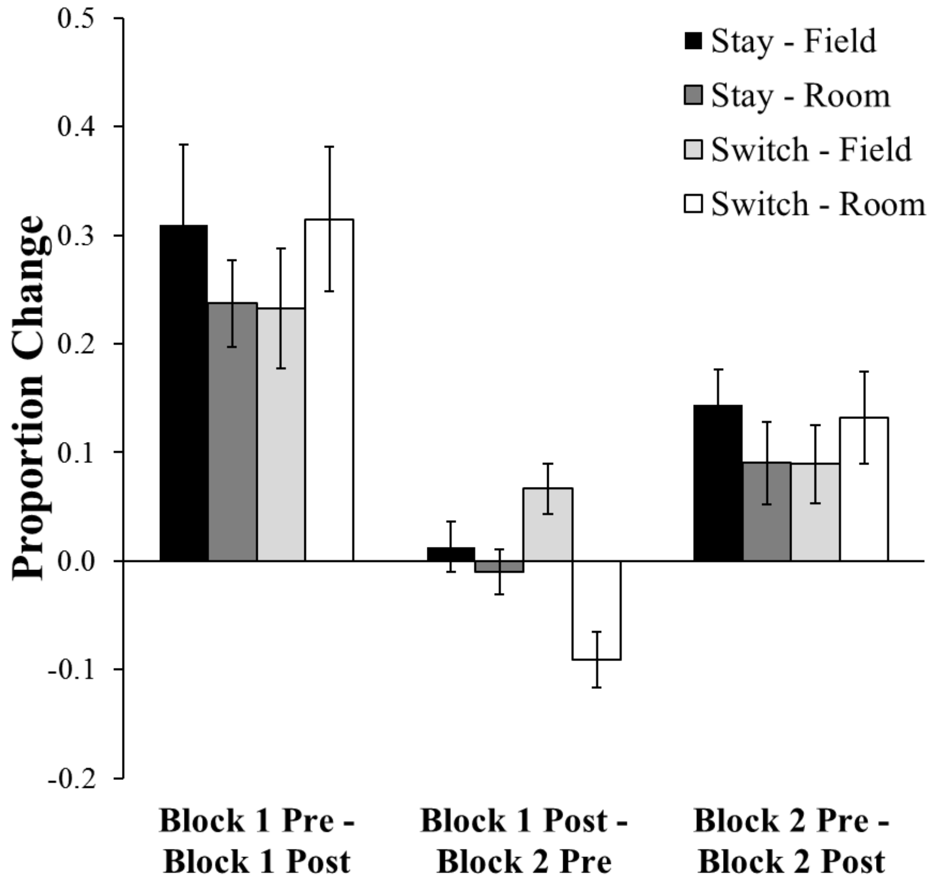

Figure 7. *Experiment 1 – Proportion change between each specified test. 1st Pre-1st Post represents initial recalibration. 1st Post – 2nd Pre represents transfer if applicable. Finally, 2nd Pre – 2nd Post represents recalibration from the second interaction. Error bars represent standard error.*

The amount of video game hours played showed no effect on initial proportion of distance walked, proportion change from first pre-test to first post-test (recalibration), or proportion change from first post-test to second pre-test(transfer). Because half of the participants were placed in conditions where the transfer measure was irrelevant, the effect of video games on first pre-test and recalibration were tested separately from the effect on transfer.

A three way MANOVA was performed on proportion of distance walked in first pre-test as well as recalibration with independent variable factors for video game hours played per week, sex, and mental rotation task score. No significant main effects or interactions were found. A three way, between subjects ANOVA was conducted on proportion change in distance walked between the first post-test and second pre-test with factors for video game hours played per week, sex, and mental rotation task score. Again, no significant main effects or interactions were found.

Discussion

The stay condition serves as a replication of previous studies (Kelly et al., 2013; Kelly et. al, 2014; Richardson & Waller 2005; Waller & Richardson, 2008) which show that interacting with a virtual environment improves distance perception. Participants improved in accuracy after each interaction with nominal diminishing returns. However, when switching from the room to grass, participants improved again solely due to the change in environment.

In the switch condition, the pattern of distance perception changed depending on which environment the participant started in. Participants who learned on the grassy field showed improved accuracy after the room was changed, despite no intervening interaction. This may be due to linear perspective created by the chosen floor and wall textures, and by the intersections between the walls and the ground and ceiling (Sedgewick, 1986). The room (figure 2) has a tile floor with rectilinear tiles while the grassy field (figure 1) has a noisy texture with no clear lines. Additional work by Wu, He, and Ooi (2007) has confirmed that linear perspective, specifically converging lines, can provide a strong cue for distance perception. Because the lines on the tiled floor and the lines created by intersecting planes would converge as distance increased, participants may have been picking up on the linear perspective, and altered their perception of distance accordingly.

By contrast, participants who started in the room were lost accuracy after switching to the grassy field. Even though perceptual accuracy was reduced when switching environments from the room to the field, the second pre-test still shows significant improvement after interaction and better accuracy than the first pre-test, so some improvement was transferred even though the exact amount of transfer cannot be determined. Experiment 2 was designed to further examine if the improved distance perception in the room environment was primarily caused by the ground texture, the walls, or both cues.

From these results, we can conclude that the interaction task is, at the very least, somewhat universal with regard to environment. The improvement in proportion of distance walked in the field to room switch (.07) is a near mirror of the reduction in the room to field switch (-.09). Because a zero-sum would be expected if improvement due to interaction transferred perfectly, it is possible that the interaction task yields improvement universally across environments while the differences between the two switch conditions are explained by the relative amount of distance cues available. Experiment 2 serves as a follow up to this experiment, specifically to identify the walls, floor, or combination of the two drives the difference between the two environments used in this experiment.

According to the results, video games had no significant effect on the relevant measures collected in this experiment. In this light, we can safely assume that simply being familiar with video games is not enough to affect distance perception in VR. We can also assume that whatever training the average gamer receives is not enough to alter their perception within our VR system, especially when compared to the interaction task.

CHAPTER 3: EXPERIMENT 2

Introduction

Experiment 2 was designed to better explain the results of experiment 1 with regard to the effect of initial environment on transfer of interaction-based improvements on perceived distance. In experiment 1, results indicated that there might be aspects of the room environment which facilitated distance perception and therefore caused the improvement in accuracy after switching from the grass to the room as well as the decrement when going from the room to the grass.

The two primary differences between the room and field environments in experiment 1 were the textures used for the ground surface and whether walls were present or not, both of which may have provided linear perspective cues that improved distance perception. To better examine the effects of these differences on distance perception and on transfer of improvement caused by interaction, experiment 2 consisted of four environments, the original two (grassy plane, and room) but also two combined environments (grassy floor with walls and tile plane without walls). Participants interacted with one of the four environments before being tested in all four environments. Similar to the first experiment, we hypothesize that adding walls and a tile floor will improve distance perception due to the addition of linear perspective distance cues, leading to a rise in accuracy for each cue added.

We also expect to see a similar pattern of improvement and decrement based on environment that we did in experiment 1. For example, the amount of improvement in experiment 1 when switching from grass to the room was similar to the amount of decrement when switching from room to grass. By the same token, we would expect the magnitude of improvement from switching from grass/no wall to grass/wall to be similar to the magnitude of accuracy lost when switching from grass/wall to grass/no wall.

Method

Participants

Seventy-four undergraduate students from Iowa State University participated in this study for course credit. Participants were randomly assigned to one of four conditions and gender was approximately balanced across condition. Two subjects were removed from all analyses due to equipment failure. Two participants failed to complete the study due to motion sickness and were removed from all analyses. One participant was excluded because the HMD headband was too small. One participant did not complete the study because the HMD caused too much unease for the participant to provide accurate responses. Finally, one participant was removed from all analyses because they were stopped from walking too far and hitting the back wall. It was not possible to verify that the participant was not artificially shortening their steps to avoid reaching the wall again. In total, seven participants were removed and all results are based on the responses from sixty-seven participants

Stimuli and Design

The virtual environment was displayed using the same virtual reality system used in the first experiment. The grass/no wall environment was identical to the grassy plane in experiment 1. Similarly, the tile/wall environment was identical to the room in experiment 1. The grass/wall environment used the grassy ground texture with the walls from the room added. The tile/no wall environment used the tile texture on the ground, but did not have any walls, continuing on into infinity like the grass plane from experiment 1.

Participants performed a pre-test and interaction block as in experiment 1. The number of trials per block (pre-test, interaction, post-test) were also identical to experiment 1. The environment used for pre-test and interaction was manipulated between participants. After the interaction, participants performed 4 post-tests, one in each environment. Order of post-test environment was counterbalanced using a 4x4 balanced Latin square. The post-tests were conducted sequentially with no additional interaction provided.

Results

Proportion change in distance walked was analyzed using a mixed-model ANOVA with between subject terms for presence of walls at training (present, absent) and ground texture at training (grass, tile) as well as within subjects terms for presence of walls at test (present, absent) and ground texture at test (grass, tile) see table 5. Due to the large number of potential effects, an alpha of .01 was selected for all statistical tests. Significant main effects of wall presence at test $F(1,63) = 76.637$, $p < .001$, $\eta_p^2 = .549$, and wall presence at training $F(1,63) = 25.174$, $p < .001$, $\eta_p^2 = .286$ were qualified by a significant interaction of wall presence at training, ground texture at training, and wall presence at test $F(1,63) = 10.323$, $p < .001$, $\eta_p^2 = .141$.

Further analysis indicates that pre-test judgments were more accurate in the two walled environments (M = 0.75, SD = .125) compared to the two environments without walls (M = 0.67, SD = 0.145); t(65) = 2.334, p = .023.

In light of the significant three way interaction and the higher pretest accuracy in the walled environments, the data were split based on the presence of walls at training and two separate mixed-model ANOVAs were conducted with a between subject term for ground texture at training (grass, tile) as well as within subject terms for presence of walls at test (present, absent) and ground texture at test (grass, tile) see tables 6 and 7.

For participants who had walls present during training, a significant main effect of wall presence at test $F(1,31) = 36.640$, $p < .001$, $\eta_p^2 = .542$ was qualified by a significant interaction between wall presence at test and floor texture at training $F(1,31) = 12.881$, $p = .001$, $\eta_p^2 = .294$. For participants who did not have walls present during training, the only significant effect was a main effect of wall presence at test $F(1,32) = 41.329$, $p < .001$, $\eta_p^2 = .564$.

Two comparisons were conducted to determine the effect of staying with the wall status from interaction versus switching to the opposite. Results show that participants performed significantly better post no-wall interaction when switching to a walled environment (M = .931, SD = .141) than when staying in a non-walled environment (M = .886, SD = .152); t(33) = 5.948, p < .001. Participants also performed worse after a walled interaction when switching to a no-wall environment (M = .842, SD = .145) than when staying in the walled environment (M = .881, SD = .160); t(32) = -4.953, p < .001.

Discussion

Before examining the effect of environment on transfer, it is important to notice that participants who had walls present during pre-test walked, on average, 8% of the intended distance farther than those without the walls. Because this test was conducted before any interaction, we can conclude that the addition of walls improves distance perception within the virtual environment by a modest amount. This replicates the pre-test results from experiment 1 where participants in the room walked farther than participants on the grassy plane. However, this effect is limited to the walls only as, contrary to prior speculation, there was no significant effect of floor texture on pre-test scores.

This difference in pre-test performance can explain the difference in improvement between the walled and non-walled interaction groups in experiment 2. Participants who interacted in an environment without walls improved more after the interaction task than participants who interacted with a walled environment, possibly because they had more room to improve.

As can be seen in figure 8, after interacting in an environment with walls and a tile floor, performance worsened when switching to either of the environments without walls irrespective of floor texture. However, when the training environment was walled with a grassy floor texture no such decrease was found. Though speculative, it is possible that the grass provided a more useful texture gradient that helped protect performance after removal of the walls while not directly improving performance. Unfortunately, the data do not provide a clear answer as to why this interaction exists.

When collapsed over distance and floor texture, participants who took their pre-test in and interacted with walled environments walked an average of 88.6% of the target distance in walled post-tests. Similarly, participants who took their pre-test in and interacted with non-walled environments walked an average of 88.2% of the target distance in non-walled post-tests.

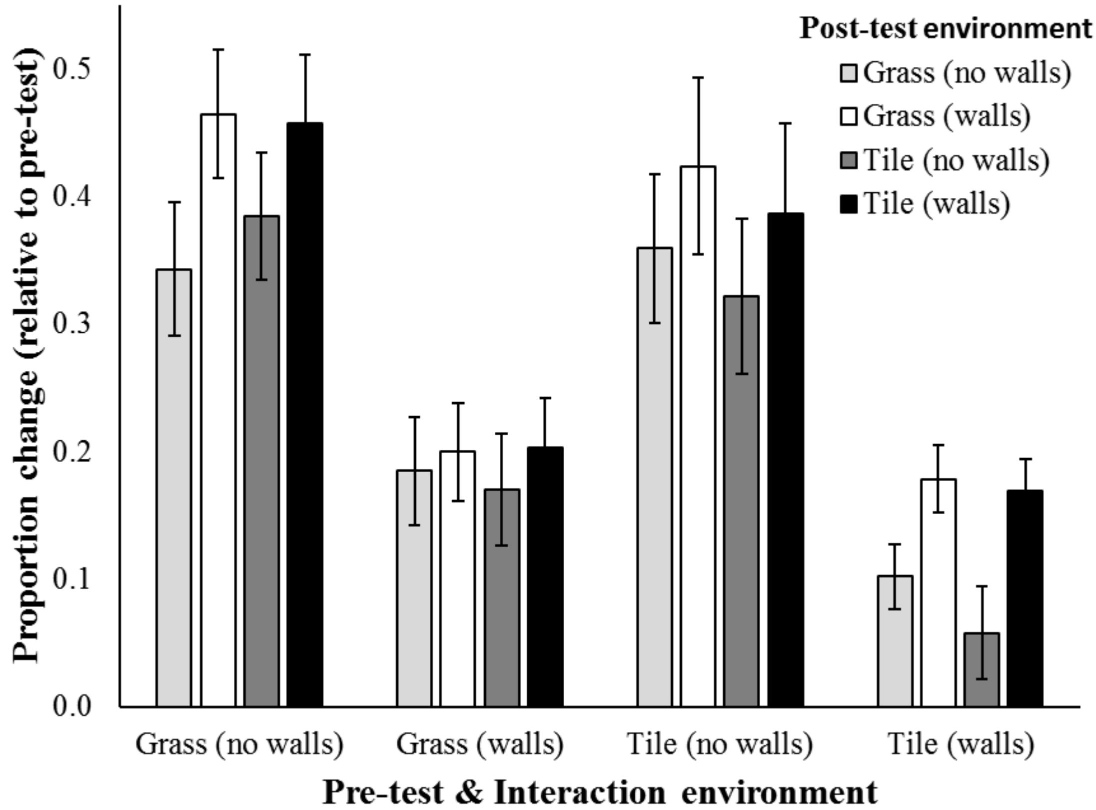

Figure 8. *Experiment 2 – Proportion change from pre-test to each individual post-test. Error bars represent standard errors.*

This similar level of post-test performance despite the significant pre-test difference supports the idea that participants who studied in no-wall environments improved more because they initially had more room to improve. When switching from a walled pre-test/interaction to non-walled post-test, participants performed significantly worse than when they stayed in the walled environment, suggesting that this decrement is due to reliance on the wall cue learned during the interaction. After the cue was removed, participant performance suffered in a way it would not have if the participant had simply interacted with the no-wall environment. When switching from a non-walled pre-test/interaction to a walled post-test environment, participants performed significantly better than when they stayed in a non-walled condition, suggesting that walls in this condition improved performance in the same way they improve pre-test performance. These effects better inform the switch conditions of experiment 1. In experiment 1, the walls and floor were inseparable when comparing the effect of switching environments after interaction, but this experiment provides evidence for walls both boosting performance when newly added and reducing performance when taken away from participants who had come to rely on them.

To generalize this finding, participants who interact with an environment that has few distance cues will benefit from switching to a cue-rich environment. However, if the participant interacts with and environment that has many cues, and then switches to an environment which lacks those same cues, some of the benefit of the interaction will be undone and performance will suffer. When applying this finding to create a general interaction task that could be used before experiencing a new virtual environment, it is important to ensure that the interaction environment does not possess distance cues that are missing from subsequently experienced environments. However, an interaction environment can be designed more sparsely than the subsequent environment because additional cues experienced after interaction will only improve distance perception.

Experiment 2 has expanded on the results from experiment 1, suggesting that the presence of walls is driving the effect we see in the switch condition while floor texture was found to have minimal impact on our tests. The observed pattern of improvement and decrement when switching to or from walled environments suggests it is likely that the interaction works, in part, because it causes the participant to notice and subsequently rely on certain distance cues to help improve performance.

While the first two experiments make a strong case for the transfer of interaction-based improvement in distance perception from one environment to another, there remains a question about the task-specificity of this improvement. Experiment 3 will examine whether or not this improvement is unique the specific interaction behavior or if that benefit carries over to all tasks performed in the virtual environment.

CHAPTER 4: EXPERIMENT 3

Introduction

In experiments 1 and 2, walking interaction produced more accurate blind walking judgments of perceived distance. Experiment 3 examined whether increases in perceived distance due to walking interaction transfer to other (non-walking) responses that indicate perceived distance, such as object size judgments, and whether changes in perceived size caused by walking interaction generalize to object distances beyond those experienced during walking interaction. Based on the size-distance invariance hypothesis (Sedgwick, 1986; Kelly, Donaldson, Sjolund, & Freiberg, 2013), perceived size is directly related to perceived distance. In this way, size judgments can be used to infer perceived distance, herein referred to as size-based distance judgments.

This experiment was designed as a replication and extension of the study reported by Kelly et al. (2013) where improvement in size-based distance judgments after walking interaction indicated that interaction caused rescaling of the perceived environment, rather than only recalibrating the walking response. In Kelly et al. (2013), participants reported perceived size verbally (e.g., “The sphere is six inches in diameter”), but size-based distance judgments were far more variable than the blind walking distance judgments, perhaps due to individual differences in the scale (e.g., participants may not have a clear idea of the units of measurement) or verbal reporting ability. Furthermore, size-based distance judgments reported by Kelly et al. (2013) were significantly smaller than blind walking distance judgments, perhaps due to participants’ unfamiliarity with verbally reporting size. Finally, the effect of walking interaction (on both walking and size judgments) was somewhat smaller than reported elsewhere, and so these findings warrant replication.

In this experiment, participants performed the same walking interaction task and blind walking distance judgments as in experiments 1 and 2, but they also made size judgments used to infer perceived distance. Instead of verbally judging object size, participants used a handheld controller to actively resize a familiar virtual object, a size 5 soccer ball resting on the ground, until it appeared to match the known physical size of a soccer ball. The resizing task is superior to the verbal judgment because individual proficiency in estimating physical units of measure will not affect final results. By allowing participants to actively scale the object until it appears to be the correct size, only perceived distance to the object should influence the final response.

There are four questions of interest that will be answered by this experiment. First, do blind walking judgments improve as a result of walking interaction? This will serve as a replication of the prior experiments as well as a manipulation check ensuring that the walking interaction is indeed having an effect. Second, do resizing judgments improve as a result of walking interaction? This will allow a diagnostic judgment as to whether improved blind walking performance after walking interaction is due to recalibration of the response or rescaling of the perceived space. Third, do improvements in blind walking performance exceed improvements in resizing performance as a result of walking interaction? Larger improvement for the blind walking task would indicate a recalibration component to improvement that is independent of rescaling. Fourth, will improvements in resizing judgments occur only for the range of distances experienced during walking interaction, or will improvements generalize to distances farther than those experienced during walking interaction? This question has been included because Kelly et al. (2014) found that walking judgments only improved for distances experienced during walking interaction

Method

Participants

Thirty-three undergraduate students from Iowa State University participated for course credit. Five participants were removed from all analyses due to equipment failure. An additional participant was removed from all analyses because they reported artificially shortening walking distances after the experimenter prevented them from walking into the far laboratory wall.

Stimuli and Design

The virtual environment was displayed using the same VR system used in experiment 1 and 2 utilizing the grassy plane environment without walls. The blind walking pre-test was the same as the pre-test from experiment 1, as was the walking interaction. Participants observed a target post and then walked to its position after the screen went blank. For the resizing test, participants looked at a soccer ball displayed at one of several distances (1m, 3m, 5m, 7m, and 11m) and resized it using two pairs of buttons on a wireless joystick that allowed both gross and fine size adjustments. The first set of button pairs on the joystick increased or decreased the radius of the ball in increments that were one percent of actual (.11cm). The second set of button pairs increased or decreased the radius of the ball in increments that were ten percent of actual (1.1cm). The initial size of the ball was randomly selected to be a value between 30% and 300% of actual. When the participant was satisfied with the object size, the experimenter initiated the save command which also advanced to the next trial. The target distances for the resizing task (1m, 3m, 5m, 7m, 11m) differed from the blind walking distances (1m, 2m, 3m, 4m, 5m) in order to examine improvement in distance judgments beyond the physical confines laboratory space. Some overlap in the distances was included in order to enable direct comparisons between the two tasks.

After participants entered the lab, they were allowed to hold a size 5 soccer ball before it was placed on the other side of the room (roughly 5 meters away). This opportunity to see and hold the ball ensured that participants knew the actual size of a soccer ball prior to making size judgments in the virtual environment. The physical ball was not visible once participants entered the virtual environment. Participants then put on the HMD and remained in the virtual environment for the duration of the study. The resizing pre-test was followed by the walking pre-test and interaction. After interaction, a resizing post-test was followed by a walking post-test.

Results

Size judgments were converted into proportion of actual distance size-based judgments under the assumption of size-distance invariance. Proportion of actual distance judged as a function of actual object distance for the walking task and resizing task are shown in figures 9 and 10, respectively. Five planned contrasts were conducted based on the existing research questions.

The first contrast examined the difference in proportion of actual distance walked between the pre and post-tests. Participants walked a significantly larger proportion of the actual distance during the post-test ($M=.133$, $SD = .142$); $t(25) = 4.770$, $p < .001$.

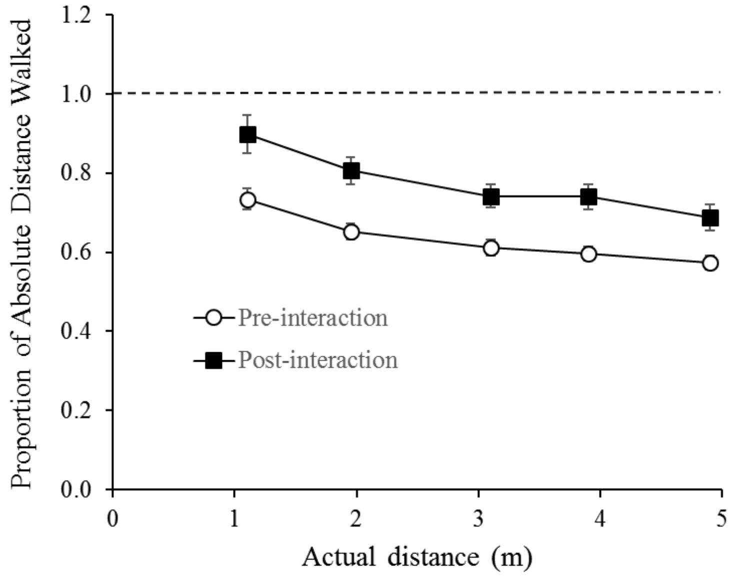

Figure 9. Experiment 3 – Proportion of actual distance walked as a function of target distance. Error bars represent standard error that contain between subject variability.

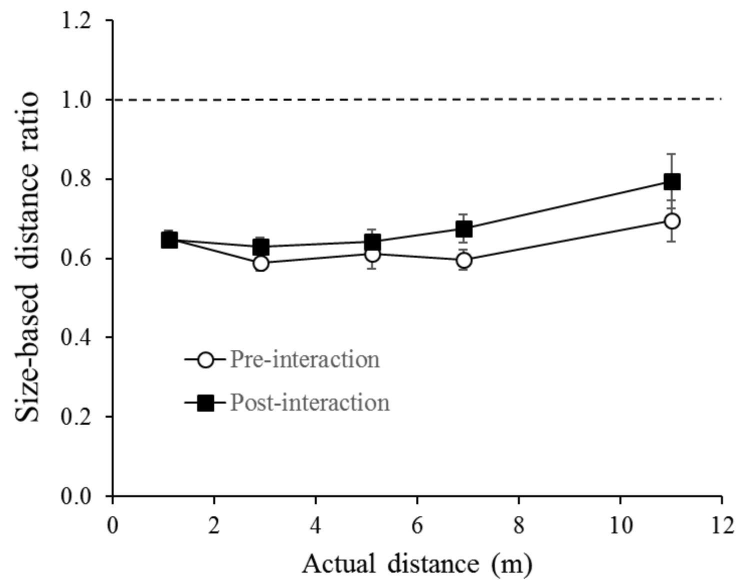

Figure 10. Experiment 3 – Ratio of sized-based distance judgment to actual as a function of target distance. Error bars represent standard error that contain between subject variability.

The second contrast examined the difference in proportion of actual distance reported through pre and post-test size-based judgments. Participants reported a significantly higher proportion of actual distance during the post test (M = .043, SD = .099); t(25) = 2.205, p = .037.

The third contrast compared the difference between post-test walking and post-test size-based judgments. Judged distance improved significantly more for walking judgments as a result of interaction than for size-based judgments. (M = .135, SD = .228); t(25) = 3.032, p = .006.

The fourth contrast examined the difference between pre and post-test size-based judgments for the distances that overlapped with the interaction task (1m, 3m & 5m). There was no significant improvement between pre and post-tests for these test distances (M = .017, SD = .101); t(25) = .884, p = .385.

The fifth contrast examined the difference between pre and post-test size-based judgments for the distances that extended beyond the interaction range (7m & 11m). Participants reported significantly higher proportions of actual distance during the post-test (M = .075, SD = .191); t(25) = 1.992, p = .057.

Discussion

These results indicate that the walking interaction is again improving performance on the walking task. More interestingly, the size-based judgments from the resizing task also improve as a result of the walking training. If size-based judgments can improve from a walking interaction, recalibration is not the only product of the interaction task; the interaction must also be causing a rescaling of the perceived environment. We have replicated the rescaling effect of Kelly et al. (2013) with a separate task, giving further credence to the rescaling concept. If a walking interaction can improve both verbal report and resizing tasks, rescaling is the only option.

Although we have evidence for rescaling, recalibration also appears to be a product of the interaction task. Blind walking performance improved more as a result of the interaction than size-based judgments. Therefore, it is likely that rescaling benefited both test tasks, while recalibration of footsteps improved blind walking above and beyond the rescaling effect. If maximizing improvement from a single interaction task, that task should always match the test task so that participants can benefit from both rescaling and recalibration.

The results of Kelly et al (2014) reported that test distances beyond the interaction did not improve in a walking task. However, this experiment showed significant improvement at the 7 and 11 meter distances. These distances were not included in the walking interaction and are also beyond the physical confines of the laboratory space. It is possible that the nature of the resizing task allowed rescaling to benefit distances beyond interaction in a way that blind walking does not. Though, as Kelly et al (2014) also suggested, it is possible that the short interaction distances might not have been long enough to allow rescaling/recalibration to take full effect, preventing any possible benefit. In this study, the interaction spanned the full 5m, similar to the long interaction condition of the other study. If a walking interaction out to 5 meters was paired with walking tests at 7 and 11 meters, it is possible that we might see the same results.

Interestingly, there was no improvement in resizing performance for the distances that overlapped with the interaction task. When looking at figure 10, the 1 meter distance stands out because it shows no improvement from pre to post-test. It is possible that there is something unique about resizing at 1m that does not apply to the same distance walking measures. If the 1m distance is unique, the lack of effect might be contributing to a lack of significance for this effect. A further study with more distances would be necessary to answer this question.

CHAPTER 5: GENERAL DISCUSSION

Summary

Underperception of distance in virtual reality is a potential problem for any researchers considering experiments with outcomes dependent on an accurate perception of distance. It also brings into question whether training done within virtual environments will be applicable in the real world. While others have considered methods of improving hardware and graphical quality in a bottom-up approach, this series of experiments was dedicated to attempting a top-down method of improving distance perception.

Experiments 1 and 2 demonstrate that behavioral improvements gained through interacting with a virtual environment carry over to novel environments presented later. This is valuable for researchers and trainers alike because the interaction phase is only necessary once per session, in order to acclimate the participant to the system. The environment selected for the interaction task should only include distance cues which are present in all test environments as removing distance cues after interaction causes a decrement in performance. If some environments possess distance cues not present in the interaction, this data suggests that the participants can only benefit.

Experiment 3 suggests that interaction causes both rescaling and recalibration. While unrelated tasks will benefit from an interaction, they do not benefit as much as the matching task. When only one type of outcome measure is important, the interaction should match that measure. If more than one type of outcome measure is being collected, rescaling benefits all outcomes and the type of interaction chosen will depend on time and other resources. The diminishing returns for multiple interactions suggests that several short, unique interactions will be more beneficial than a single repeated interaction. A repeated interaction grants recalibration to one response only and rescaling to all others. Multiple, unique interactions grant recalibration to multiple responses while still providing rescaling. When time is short, researchers should feel confident that an interaction task will benefit all measures through rescaling, just not to the degree that a recalibration/rescaling combination would.

Future Directions

Future research in this area should examine the effect of walls in more detail. The lack of effect for floor texture in Experiment 2 suggests that linear perspective may not necessarily be the cause. It is possible that the presence of walls (any walls) constricts the available space and aids distance perception. Follow-up studies should examine the use of 'natural' walls such as tree lines or rock formations that lack linear perspective. Extending the benefit of walls to outdoor virtual environments would give researchers another valuable tool for improving their simulations.

Future research could also expand on the question of rescaling vs. recalibration. This study and previous research have shown a large amount of variability in the improvement for tasks not matched to the interaction. It is possible that individual differences in participants changes the amount of rescaling that occurs. This same paradigm should also be extended to other tasks such as blind throwing or other similar tasks. If rescaling is truly occurring, it should be possible to demonstrate improvement in a wide range of tasks unrelated to the interaction. Finally, demonstrating improvement in blind walking as the result of an unmatched interaction would give strong support for the universal nature of rescaling.

In conclusion, these studies show the value in performing an interaction task prior to research or training in virtual reality. While this top-down method does not entirely solve the problem of underperception, it makes great strides and could theoretically be combined with the bottom-up improvements in hardware and graphics from other researchers to facilitate a more accurate perception of distance than either method could produce alone.

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APPENDIX A. VIDEO GAME MEASURE

Principle Investigator: Jonathan W. Kelly
Title of Project: Human Navigation in Virtual Environments

Video Game Experience

On a typical school day (Monday through Friday), for how many hours do you play video games during each of the following times? (mark "0" if you don't play at all during those hours)

1. 6AM – Noon
2. Noon – 6 PM
3. 6 PM – Midnight
4. Midnight – 6 AM

On a typical weekend day (Saturday or Sunday), for how many hours do you play video games during each of the following times?

5. 6 AM – Noon
6. Noon – 6 PM
7. 6 PM – Midnight
8. Midnight – 6 AM

How often have you played the following video games? Count any video game in the series, where applicable. Please give an answer from 1 to 5 for these questions (from "1" indicating you have never played it to "5" indicating you play it very often).

9. Half-Life
10. Halo
11. Resident Evil
12. Unreal Tournament
13. Call of Duty
14. Grand Theft Auto
15. World of Warcraft or any other Massively Multiplayer Online Role-Playing Game, such as Guild Wars
16. Madden NFL
17. Wii Sports
18. Tony Hawk
19. The Sims
20. Rock Band/Guitar Hero

Which video games do you most often play? (list the titles)

21. Most often: ____________________
22. Second-most often: ____________________
23. Third-most often: ____________________

APPENDIX B. MENTAL ROTATION TASK

Principle Investigator: Jonathan W. Kelly
Title of Project: Human Navigation in Virtual Environments

Mental Rotation

This is a test of your ability to look at a drawing of a given object and find the same object within a set of dissimilar objects. The only difference between the original object and the chosen object will be that they are presented at different angles. For each problem there is a primary object on the far left. You are to determine which two out of the four objects to the right are the same object shown on the far left. In each problem, two of the four drawings are the same object as the one on the left. You are to put Xs below the correct ones, and leave the incorrect ones blank. Your score will reflect both the correct and incorrect responses, so you should not guess unless you have some idea which choice is correct.

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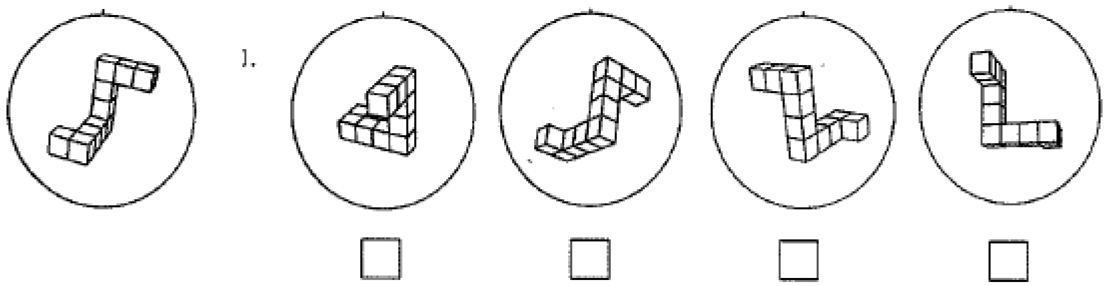

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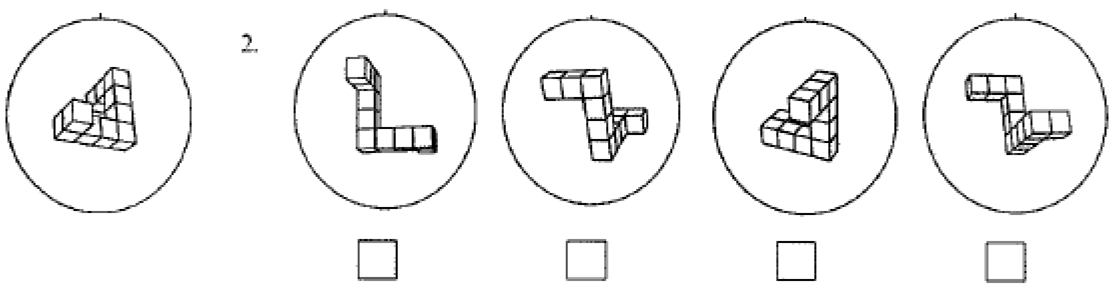

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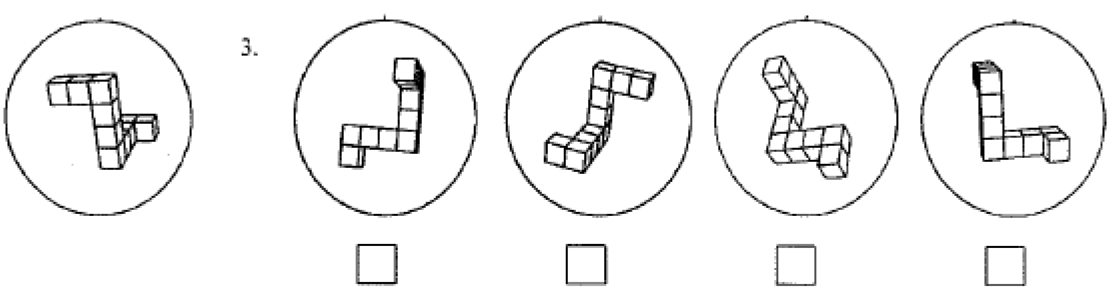
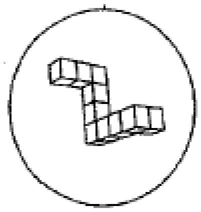
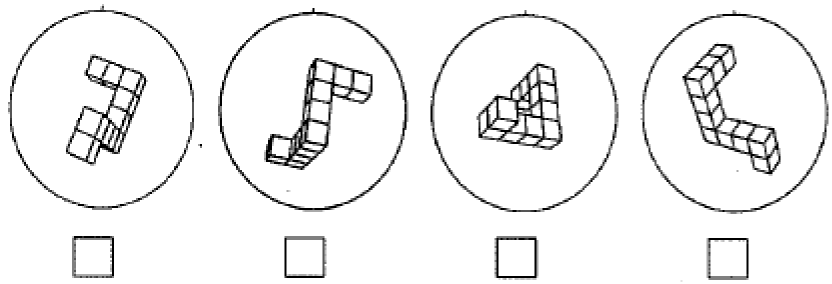
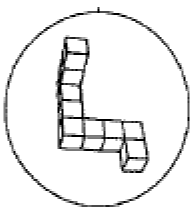




4.





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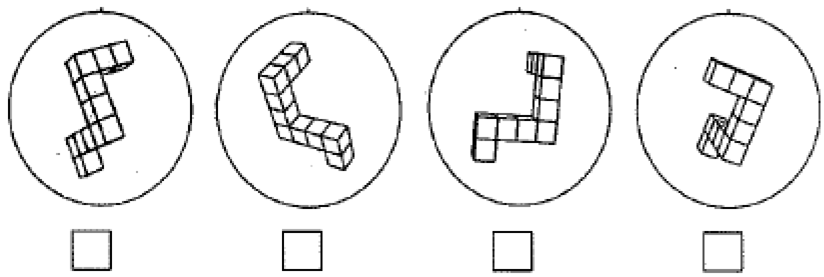

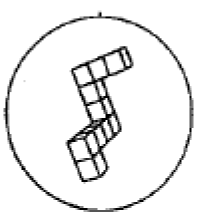

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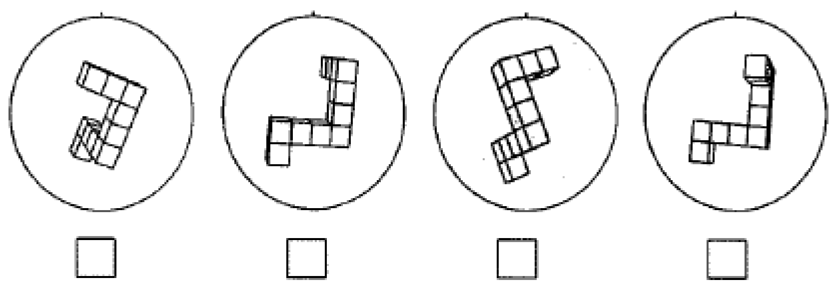

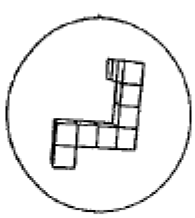

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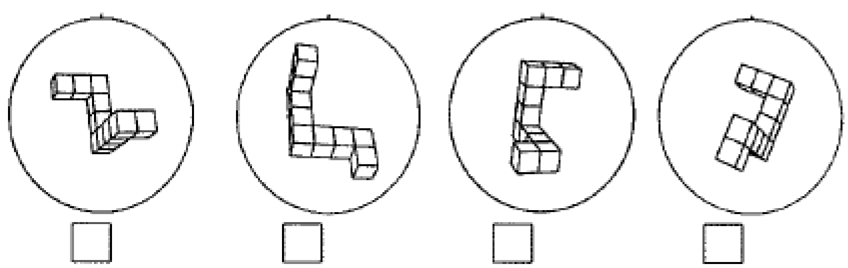

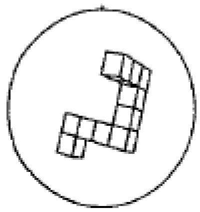

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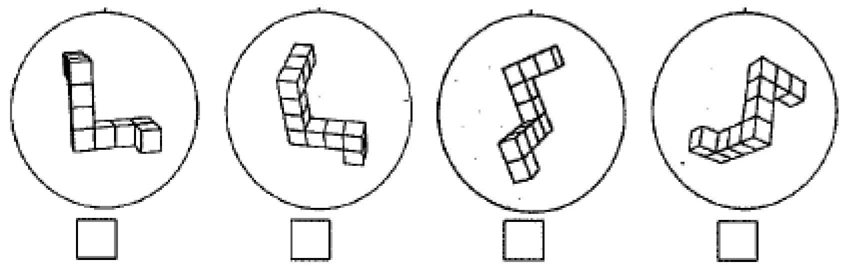

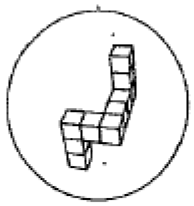

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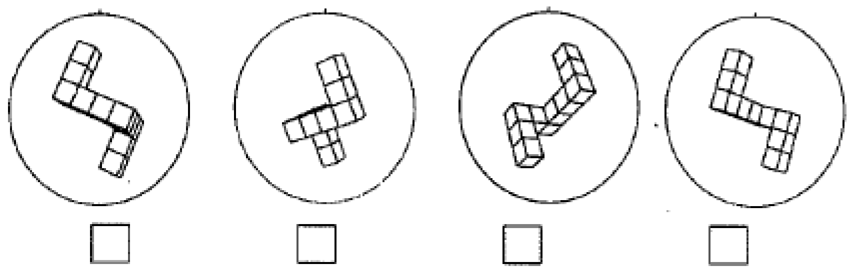

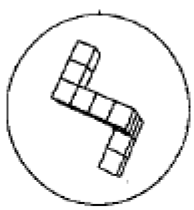

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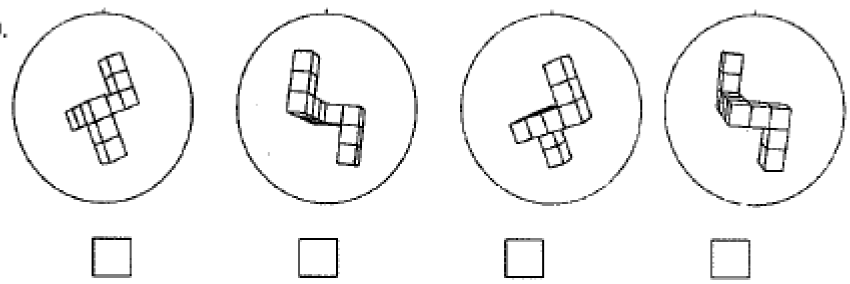

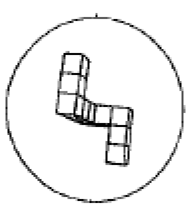

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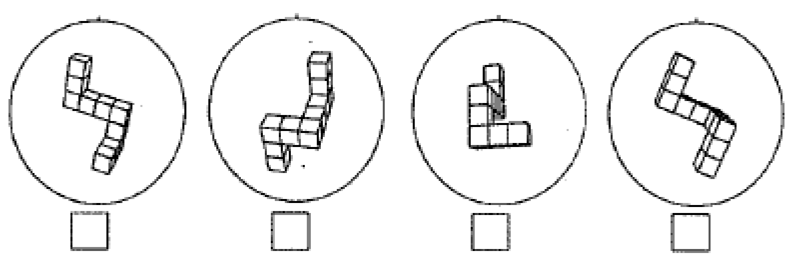

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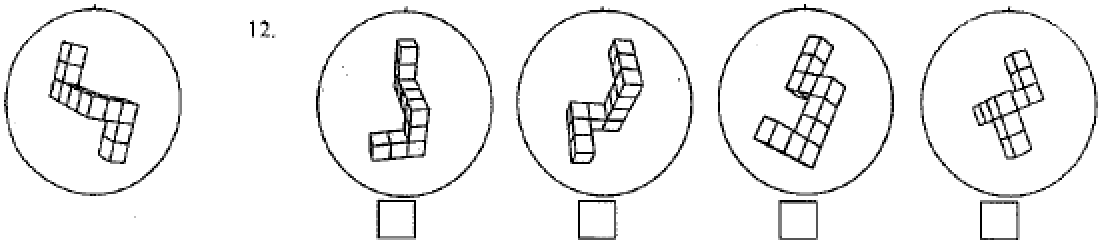

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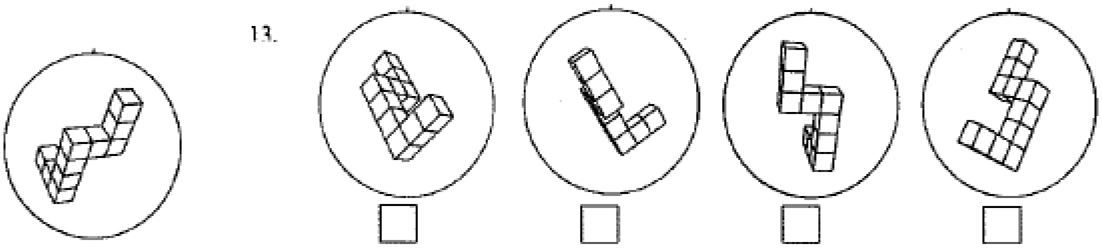

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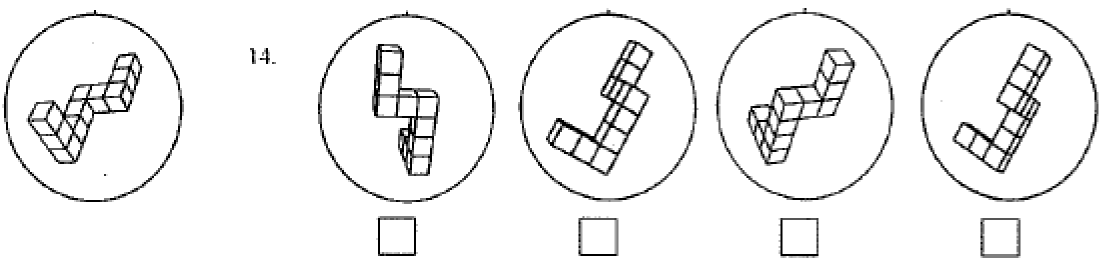

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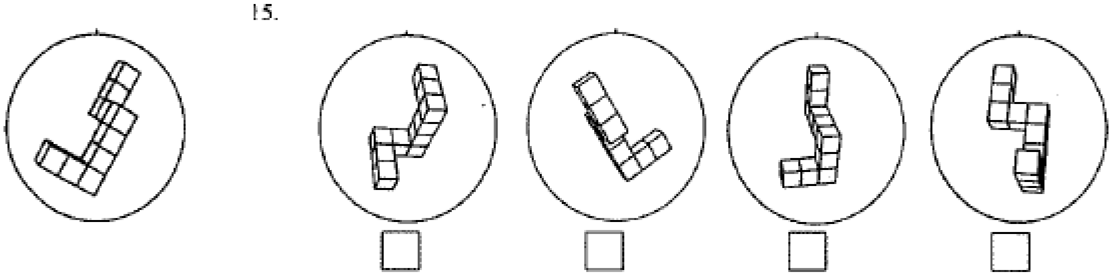

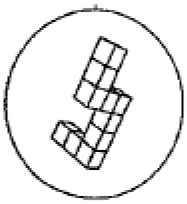

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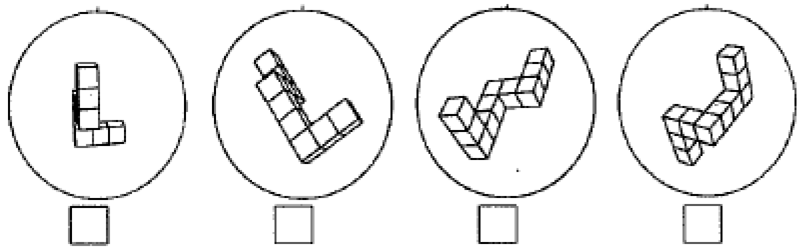

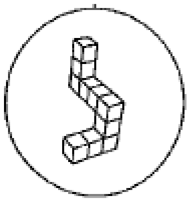

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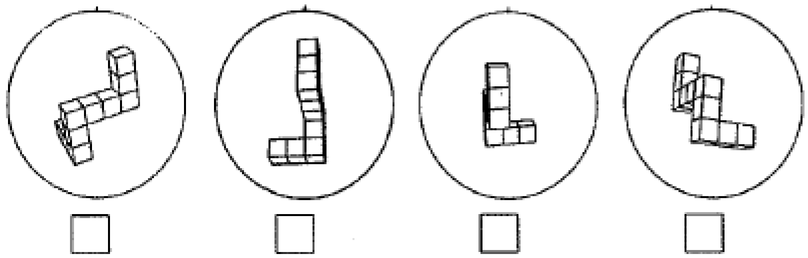

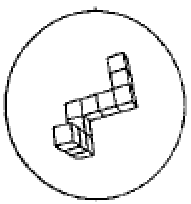

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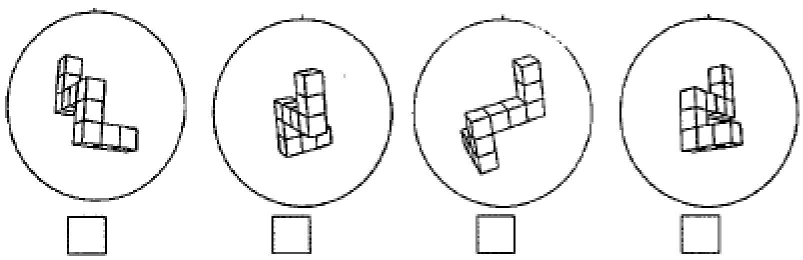

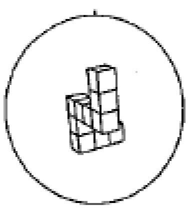

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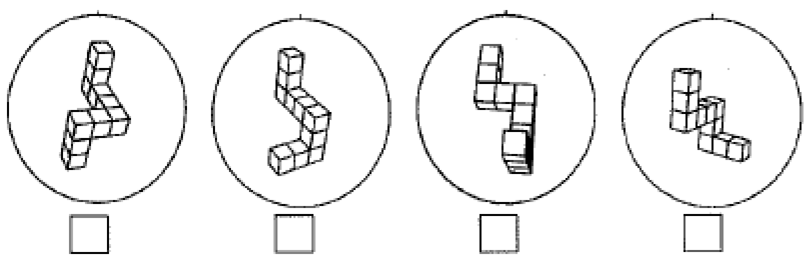

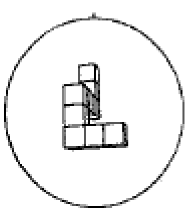

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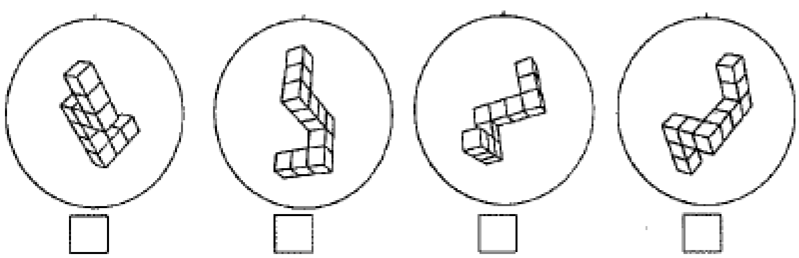

APPENDIX C. TABLES

Table 1

Experiment 1 – Four-way ANOVA on proportion of distance walked

Source	SS	*df*	MS	*F*	*p*
Condition	.053	1	.053	.143	.707
First Environment	.034	1	.034	.091	.764
Condition x first Environment	3.571	1	3.571	9.569	.003
Error (Between)	22.393	60	.373		
Test	7.527	3	2.509	53.569	.000
Test x Condition	.022	3	.007	.154	.927
Test x First Environment	.384	3	.128	2.730	.045
Test x Condition x First Environment	.089	3	.030	.635	.593
Error (Test)	8.430	180	.047		
Distance	8.224	4	2.056	94.738	.000
Distance x Condition	.045	4	.011	.522	.720
Distance x First Environment	.084	4	.021	.969	.425
Distance x Condition x First Environment	.001	4	.000	.017	.999
Error (Distance)	5.208	240	.022		
Test x Distance	.093	12	.008	1.000	.447
Test x Distance x Condition	.117	12	.010	1.270	.232
Test x Distance x First Environment	.032	12	.003	.347	.980
Test x Distance x Condition x First Environment	.208	12	.017	2.249	.009
Error (Test x Distance)	5.548	720	.008		

Table 2

Experiment 1 – Three-way ANOVA for "Stay" condition

Source	SS	*df*	MS	*F*	*p*
First Environment	1.455	1	1.455	4.442	.044
Error (Between)	9.825	30	.328		
Test	3.873	3	1.291	31.673	.000
Test x First Environment	.097	3	.032	.795	.500
Error (Test)	3.668	90	.041		
Distance	4.487	4	1.112	41.631	.000
Distance x First Environment	.051	4	.013	.477	.752
Error (Distance)	3.233	120	.027		
Test x Distance	.056	12	.005	.510	.908
Test x Distance x First Environment	.131	12	.011	1.203	.279
Error (Test x Distance)	5.548	360	.008		

Table 3
Experiment 1 – Three-way ANOVA for "Switch" condition

Source	SS	*df*	MS	*F*	*p*
First Environment	2.151	1	2.151	5.134	.031
Error (Between)	12.567	30	.419		
Test	3.675	3	1.225	23.155	.000
Test x First Environment	.376	3	.125	.2.366	.076
Error (Test)	4.672	90	.053		
Distance	3.782	4	.946	57.451	.000
Distance x First Environment	.034	4	.009	.519	.722
Error (Distance)	1.975	120	.016		
Test x Distance	.154	12	.013	2.028	.021
Test x Distance x First Environment	.109	12	.009	1.433	.046
Error (Test x Distance)	2.284	360	.006		

Table 4

Experiment 1 – Four-way ANOVA on proportion change

Source	SS	*df*	MS	*F*	*p*
Condition	.010	1	.091	.587	.800
First Environment	.218	1	.218	1.408	.240
Condition x First Environment	.091	1	.091	.587	.447
Error (Between)	9.298	60	.155		
Test	12.516	2	6.258	42.833	.000
Test x Condition	.008	2	.004	.027	.973
Test x First Environment	.438	2	.219	1.499	.228
Test x Condition x First Environment	.931	2	.466	3.187	.045
Error (Test)	17.532	120	.146		
Distance	.002	4	.000	.023	.999
Distance x Condition	.052	4	.013	.778	.540
Distance x First Environment	.030	4	.008	.455	.768
Distance x Condition x First Environment	.058	4	.014	.867	.484
Error (Distance)	3.985	240	.017		
Test x Distance	.365	8	.046	1.504	.153
Test x Distance x Condition	.308	8	.038	1.268	.258
Test x Distance x First Environment	.030	8	.004	.124	.998
Test x Distance x Condition x First Environment	.317	8	.040	1.306	.238
Error (Test x Distance)	14.555	480	.030		

Table 5
Experiment 2 – Four-way ANOVA on proportion change

Source	SS	*df*	MS	*F*	*p*
Training Floor	.218	1	.218	2.766	.042
Training Walls	.103	1	.103	1.301	.020
Training Floor x Training Walls	.061	1	.061	.382	.012
Error (Between)	4.967	63	.079		
Test Walls	.176	1	.176	68.006	.000
Test Walls x Training Floor	.002	1	.002	.926	.339
Test Walls x Training Walls	.126	1	.126	48.531	.000
Test Walls x Training Floor x Training Walls	.028	1	.028	10.779	.000
Error (Test Walls)	.163	63	.003		
Test Floor	.002	1	.002	.605	.440
Test Floor x Training Floor	.201	1	.201	60.144	.000
Test Floor x Training Walls	.000	1	.000	.117	.733
Test Floor x Training Floor x Training Walls	.015	1	.015	4.549	.037
Error (Test Floor)	.210	63	.003		
Test Walls x Test Floor	.000	1	.000	.020	.887
Test Walls x Test Floor x Training Floor	.014	1	.014	5.202	.026
Test Walls x Test Floor x Training Walls	.013	1	.013	4.893	.031
Test Walls x Test Floor x Training Floor x Training Walls	.124	1	.124	45.851	.000
Error (Test Walls x Test Floor)	.170	63	.170		

Table 6

Experiment 2 – Three-way ANOVA on proportion change for participants who interacted in environments with walls.

Source	SS	*df*	MS	*F*	*p*
Training Floor	.251	1	.251	3.187	.084
Error (Between)	2.444	31	.079		
Test Walls	.002	1	.002	.843	.366
Test Walls x Training Floor	.023	1	.023	9.280	.005
Error (Test Walls)	.077	31	.002		
Test Floor	.002	1	.002	.609	.441
Test Floor x Training Floor	.052	1	.052	15.359	.000
Error (Test Floor)	.105	31	.003		
Test Walls x Test Floor	.006	1	.006	2.224	.146
Test Walls x Test Floor x Training Floor	.027	1	.027	10.476	.003
Error (Test Walls x Test Floor)	.079	31	.003		

Table 7

Experiment 2 – Three-way ANOVA on proportion change for participants who interacted in environments without walls.

Source	SS	*df*	MS	*F*	*p*
Training Floor	.025	1	.025	.311	.581
Error (Between)	2.523	32	.079		
Test Walls	.305	1	.305	112.836	.000
Test Walls x Training Floor	.007	1	.007	2.622	.115
Error (Test Walls)	.086	32	.003		
Test Floor	.000	1	.000	.098	.757
Test Floor x Training Floor	.166	1	.116	50.309	.000
Error (Test Floor)	.105	32	.003		
Test Walls x Test Floor	.008	1	.008	2.681	.111
Test Walls x Test Floor x Training Floor	.112	1	.112	39.611	.000
Error (Test Walls x Test Floor)	.091	32	.003		