Encoding Height: Egocentric Spatial Memory of Adults and Teens in a Virtual Stairwell

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ABSTRACT

Commodity-level virtual reality equipment is now available to all ages. To better understand how cognitive development affects people's spatial memory in virtual reality, we assess how adults (20-29 years old) and teenagers (14-17 years old) represent their spatial memory of objects in an immersive virtual environment (IVE) where height is encoded. Despite virtual reality being a favorable conduit for the study of egocentric spatial memory, prior studies have predominately looked at objects placed at similar heights. Within a stairwell environment, participants learned the positions of nine target objects. In one condition, all objects were placed near eye height. In another, they were placed at varying heights. Our results indicate that participants' errors and latencies were similar in both environments, and across age groups. Our results have implications for the development of IVEs and the expansion of immersive technology to a more diverse, younger audience.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Empirical studies in HCI**; • **Applied computing** → *Psychology*.

KEYWORDS

virtual reality, virtual environments, spatial memory, height perception, cognitive development, perceptual development

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Virtual reality (VR) is becoming more accessible to a larger, diverse population, and yet we do not have a sufficient understanding of how these new users, including children and the elderly, experience immersive virtual environments (IVEs). Commodity level IVEs allow exciting opportunities for entertainment and education. However, the growing popularity of VR with young consumers is concerning as less is known about how young users perceive IVEs. A corollary to this concern is that the equipment is getting better: we have higher resolutions and wider fields of view. The equipment is also lighter and more affordable, making the technology increasingly accessible to young audiences. It is crucial to study the impact of IVEs on children's spatial perception as cognitive development may affect the way they reason about spaces in virtual reality. In particular, by studying children's spatial learning and orientation in VR, we may better design immersive applications to optimize their perceptual abilities, thereby increasing engagement and optimizing the benefit of learning applications for VR.

People remember the places they traverse in everyday life. Some indoor and outdoor environments include chances to explore in relatively flat places and other environments include changes in elevation due to stairs, ramps, and hills. There are numerous studies on spatial learning with adults in virtual and real environments that are flat, e.g., [Lawton 1996; Weisberg and Newcombe 2014; Wen et al. 2013; Williams et al. 2007], numerous studies with children in physical environments that are flat, e.g., [Bullens et al. 2010; Huttenlocher et al. 1994; Ribordy et al. 2013; Rieser et al. 1994], and only a few studies with children in immersive virtual environments simulating flat areas [Negen et al. 2016; Petrini et al. 2016].

Much is known about the spatial processes through which adults and children learn spatial layouts when height need not be encoded e.g., [Kelly and McNamara 2008; Narasimham et al. 2018; Rieser et al. 1994, 1986; Williams et al. 2007], but less is known about how people encode the vertical positions of objects in space for spatial orientation, e.g., [Holmes et al. 2015; Kelly 2011]. Theoretically, the two learning situations may differ. For example, one could theorize that learning a vertically distributed array would be more difficult, because it would require the integration of distances and directions including height. On the other hand, one could argue that objects distributed when height was invariant would be more difficult to learn, because they would differ only by angles and distances in two dimensions, not three. Our motivation to study height arose from studies that have examined the encoding of slope [Holmes et al. 2015; Kelly 2011] which provides cues about height and distance; however these studies did not directly assess height.

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In day to day life, height encodings are useful for navigation and searching tasks. For example, people must understand the heights of objects to reach for food on the top shelf in a grocery store, to estimate the heights of buildings or trees, and to understand their surroundings while hiking to the summit of a mountain. Several studies have assessed subjects' egocentric and allocentric spatial memory in both real and virtual environments [Kelly and McNamara 2008; Narasimham et al. 2018; Riecke and McNamara 2017; Rieser et al. 1994; Williams et al. 2007]. However height has not been a factor in these studies, i.e., the objects were presented at invariable heights, or along a single axis relative to a participant. Our current research investigates spatial memory for objects at different heights.

We are aware of no studies that have investigated spatial learning of children and adults of landmarks in virtual environments that include changes in elevation. Our current study addresses this gap in literature by evaluating spatial memory across two environments based on a bending stairway. University students and high school students were asked to study the locations of nine everyday target objects in one condition where they viewed them all arranged at eye level, and in a second condition in which target objects were placed above, below and at eye level. These were called the "targets distributed horizontally" (TDH) and the "targets distributed vertically" (TDV) conditions, respectively.

Our work was inspired by a recent experiment by Asjad et al. [2018], which explored people's perception of height while ascending an infinite virtual staircase. In the current study we examine whether participants, both adults and teenagers, would remember objects placed at different heights better, such as in multiple levels of a stairwell (i.e., the "targets distributed vertically" condition), than objects places at the same height, within one level of the stairwell (i.e., the "targets at eye height" condition).

This study also builds on Narasimham et al. [2018], where children and teenagers were tested on a simple spatial memory task. The participants learned the layout of five wall posters in either a real world lab or in a corresponding immersive virtual environment (IVE), and they were tested on their memory by either imagining a perspective change or through a physical perspective change. Participants of both ages found remembering in the imagined perspective harder and took longer to complete trials. However, there was no significant difference in spatial memory between participants that learned the layout of the real world environment versus those who learned the layout of the virtual environment. We believe this result encourages the use of a virtual environment for evaluating spatial memory in teens in the current study. Although, we believe that pursuing spatial memory studies in real world environments is also desirable. In particular, it may be necessary for investigations involving young children who find contemporary, immersive head-mounted displays (HMDs) heavy. In the current study we test participants on a basic memory test without perspective change, but with more objects, placed at varying heights.

This study is our first of children and adults trying to learn the locations of objects distributed across a large, walkable three-dimensional space. Our questions are two-fold: can participants, especially the younger participants remember all the locations? And second, does spatial memory benefit from the additional information provided by height information? This is a novel approach — using stairs, in an IVE, to study spatial memory. We therefore evaluated the efficacy of the environment itself before we begin using this for other spatial memory tests.

1 BACKGROUND

1.1 Experiments with children in virtual environments

Light weight and ergonomic commodity-level virtual reality hardware has only been available for a few years. The previous generation of virtual reality equipment was not readily available or usable by children. Thus, little is known about how children reason and spatially learn in an immersive virtual environment. Plumert, Kearney and colleagues have studied children's actions and affordances in large screen immersive environments for a number of years. A recent review of their findings can be found in Plumert and Kearney [2018]. Morrongiello et al. [2015] studied gap crossing affordances in virtual reality for children. O'Neal et al. found that 14 year-olds had the same performance as adults in a perception-action task in a large screen immersive virtual environment. The lower range of our subjects is 14. We decided to test this range not because we doubt the results of O'Neal et al., but because we employ a head-mounted display as our testing device and wanted to insure that our subjects could deal effectively with the moving up and down stairs in this device.

1.2 Spatial memory tests

Spatial memory tests typically involve learning a layout from one perspective and recalling details about the layout from the same or different perspectives [Kelly and McNamara 2008; Narasimham et al. 2018; Rieser et al. 1994, 1986; Williams et al. 2007]. In a prototypical study, Rieser, Guth, & Hill [1986] asked participants to view targets in a room from one observation point, and imagine themselves at other points. They were asked to determine target locations from the original observation point, and also by walking to the second viewpoint, or by imagining themselves at the second viewpoint. Participants performed better when they physically walked, than when they imagined, and their performance was mediated by a "dynamic imagery strategy," where they updated their representations when walking. Rieser et al. [1994] tested children and adults on a similar task, and showed a similar advantage of locomotion over imagination.

Several studies have compared both children's and adults' performance on these spatial memory tests in physical environments. But how does the virtual environment compare? Williams et al. [2007] demonstrated that participants were similar in their judgments of locations after exploring either a virtual or physical environment. The errors were worse on trials where they had to imagine a different perspective but participants were faster and more accurate on trials when they physically rotated or translated to the different perspectives. Further evidence comes from Narasimham et al. [2018], who tested 14-17 year old teenagers and 9-12 year old children on tasks modeled after Rieser et al. [1994] and Williams et al. [2007], in both an IVE and a physical environment. There was no difference of age, or of the environments in participants' spatial memory. As before participants took longer and were less accurate on the imagination trials. There was a robust advantage to physical

Figure 1: A participant explores the virtual stairwell environment with tetherless position tracking using the HTC Vive Pro

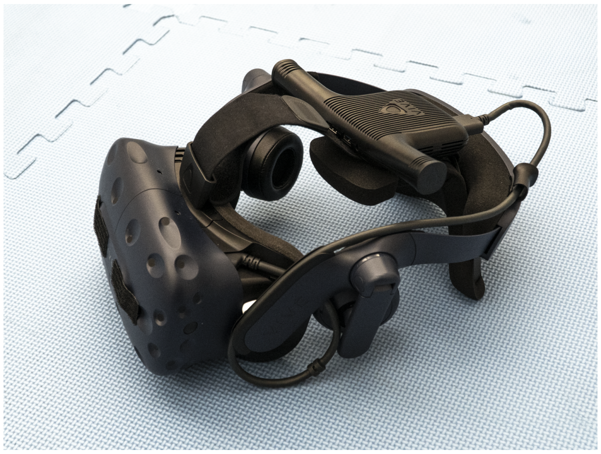

Figure 2: A closeup view of the HTC Vive Pro and Wireless Adapter

locomotion in updating spatial representations, even in the virtual environment.

1.3 Current study

How does the VE affect spatial memory when locomotion will be over heights, such as stairs? Although virtual spaces have been designed for many kinds of movements such as walking on treadmills [Iwata 1999], walking-in-place [Slater et al. 1995], using gestures [Lai et al. 2015], and walking with both passive [Asjad et al. 2018; Nagao et al. 2017] and active [Nordahl et al. 2010] haptics, there have been few looking at displacement over height. In most of these experiments, the VE works by coupling eyeheight manipulation with a motor action, either a walking locomotion or a gesture. Asjad et al. [2018], explored how well people estimated height while ascending or descending an endless virtual staircase. They found that people were able to navigate a stairs environment, and estimate heights, findings relevant to this paper. Other experiments have shown people experience some fear of heights in open spaces (Stefanucci & Proffitt [2009]), so we decided to use simulations of closed stairwells, especially with children.

A three dimensional space where objects are placed at different heights could provide an advantage in aiding memory: a chandelier on the ceiling, or a clock on a wall above stairs are common; in the external environment, we routinely see billboards or bells, street lights and tall buildings. It would be strange to see a billboard at eye-height where height is encoded with the object's location. On the other hand, height may interfere: participants may find it harder to remember objects distributed at different heights. While our intuition says otherwise, it would be useful to study both location memory for objects placed at different vs. similar heights concurrently. Thus our study presented both environments in a within-subjects design.

A second question we wanted to assess was how teenagers compared to adults in this spatial memory task. Do younger subjects encode height differently than adults, i.e., does height help or hinder one group in terms of errors in location, or in the time taken for these tasks? This is relevant since some studies have shown age differences, albeit with younger children (e.g., Rieser et al. [1994]), while others have not (e.g., Narasimham et al. [2018]).

To recap, our questions are two-fold: can participants, especially the younger participants remember all the locations? Drawing from Narasimham et al. [2018], we hypothesize that age differences will be negligible; but based on earlier papers, we may find that younger participants make more errors, and are slower. And second, will there be an effect of adding the third dimension, i.e., height, on recall? This is a novel approach - using stairs, in an IVE, to study spatial memory. We expect that participants of both ages may make fewer errors, and be faster on the stairs in which targets were distributed vertically; on the other hand participants may find the stairs in which targets were placed near eye height less complicated. There may also be interactions of environment and age groups.

2 SYSTEM

2.1 Materials & Apparatus

The virtual environment was rendered using the HTC Vive Pro, a commodity level immersive virtual reality system with 1440 × 1600 per eye resolution and an approximate 110° field of view. Tetherless position tracking (Figure 1) was provided via the HTC Vive's native tracking system in conjunction with the HTC Vive Wireless Adapter (Figure 2). In order to simulate a realistic sensation of ascending and descending a stairs in virtual reality, we modified the vertical translation method designed by Asjad et al. [2018].

In the original algorithm, a participant's height was vertically translated based on a finite state machine in which the position of the user's feet influenced a linear interpolation method that moved the player up or down as they navigated through the environment. Foot position was tracked using HTC Vive tracking pucks. However, our current solution uses a more lightweight approach. Specifically, we vertically translate position as a function of the user's head

Figure 3: Stairwell for the "targets at eye height" (TEH) condition

Figure 4: Stairwell for the "targets distributed vertically" (TDV) condition

position alone. To ensure participant comfort throughout the experiment, translation thresholds were included to prevent participants from falling off of the stairs at any time.

2.2 Virtual Stairs

As we are interested in evaluating 3D spatial memory, we designed a familiar environment in which height is naturally encoded–a stairwell. The virtual stairwell environment contained three flights of stairs and was embellished with doors, windows, and other small adornments to enhance realism (See Figure 4). Outside of the windows, an expansive lake and mountainous terrain were nestled along the horizon. The exact dimensions of the flights were based on measurements taken from the main stairwell of a Feathingill Hall–a building on the campus of Vanderbilt University. The same stairwell dimensions for a flight of stairs was used in Asjad et al. [2018]. Each flight of stairs consisted of 11 steps, including a landing at the top of each flight. These flights alternated in direction and were connected by landings, which measured 93.5cm x 2.64m x 15cm. The rise and the tread of each step were 15cm and 30cm, respectively. The same stairwell environment was used throughout the current study. However, the stairwell was populated with target objects, which were varied depending on the experimental condition.

In the "targets distributed horizotally" (TDH) condition (Figure 3), target objects were placed around the user at approximately the same height. The baseline height was chosen to be 1.7m, an approximate eye height for adults. Objects were distributed vertically objects within ±0.1m of this height. For example, the basket resting on the window-sill may be at 1.8m, the soccer ball on the shelf may be at 1.6m, etc. This positioning approach mimics the strategy found in prior VR egocentric spatial memory experiments [Adamou et al. 2013; Giudice et al. 2009; Narasimham et al. 2018; Williams et al. 2007]. The small variation in heights was selected to allow for the natural placement of target objects in the environment and to better compensate for variability in participants' actual eye height. The heights were calculated from the second landing where the participant was situated during the experiment (refer to Figure 3).

In the "targets distributed vertically" (TDV) condition (Figure 4), target objects were horizontally distributed identically to the TDH condition, but the vertical variation was significantly larger. Objects were placed above, below, and near the 1.7m height such that three target objects were placed on each level of the stairs. Thus objects were arranged to be on the floor, suspended from ceiling, or high upon the walls.

Eighteen distinct items were employed in total, allowing for nine unique items for each of the experimental conditions, and all objects were positioned so that they were visible from the second landing of the stairwell. The second landing of the stairwell was selected as the point of reference from which to place all target objects, because it provided sufficient clearance for items to be placed both above and below a participant.

3 EXPERIMENT

3.1 Participants

Eight teenagers (14-17 years; M = 16 years, 5 female) and eight adults (20-29 years; M = 25 years, 4 female) were recruited for the experiment. We chose this sample size, based on our prior experiments where we obtained a small to medium effect size [Narasimham et al. 2018]. Our intention was also to test this methodology before extending to younger participants. All participants had normal or corrected to normal vision. Our experiment and methods were approved by the local institutional review board, and consent was obtained from all subjects.

3.2 Design

All participants experienced both virtual stairwell conditions. Half of the participants in each age group experienced the TDH condition first and the other half experienced the TDV condition first to help mitigate order effects.

Within each condition, participants were asked to turn to face target objects within the room from a reset point near the center of the stairwell. The reset point's position in the virtual environments is indicated by the human marker in Figures 3 and 4. Participants memorized the location of nine objects, and they were asked to turn to face the target three times each for a total of 27 trials per experimental condition. Trials were randomized such that no target object was revisited within the span of two consecutive trials.

Where environmental condition (TDH and TDV), order, and age were considered independent factors, turning error along the y-axis and latency were recorded as dependent measures. For each trial, an initial orientation was recorded near the reset target and an end orientation was recorded at the end of the participant's turn. The participant's change in orientation was recorded as the signed difference between their start and end angles. This was then compared to a perfect change in rotation between the start and end targets based on the participant's current position in the environment. Turning error was calculated as the absolute difference between a perfect change in angle and the participant's actual change in angle. Latency was recorded as the time between the start and the end of each turn.

3.3 Procedure

The entire experiment session took approximately 25 minutes. At the onset of the experiment, participants were given the HTC Vive Pro and they were asked to briefly explore the virtual stairwell. They initially spawned at the ground floor of the environment, so they were encouraged to walk up to the highest landing at least once for complete exploration. After the participant expressed that they were comfortable with the environment, they were asked to walk to a position on the second landing. At this point, the experimenter revealed which objects in space the participant needed to remember. The participant shifted into a position from which all target objects were visible.

Participants were given 180 seconds to memorize the objects. Once the subject stated that they had memorized the locations of the nine target objects, the stairwell rendering was removed. Instead, the virtual environment was replaced by a scene devoid of geometric features (Figure 5). Only a circle on the floor near the participant's feet and a target board suspended in midair near what was previously the center of the stairwell, remained. This empty space provided a controlled testing environment during the evaluation of spatial memory, for the blind pointing task. The target board in front of the user served as a marker for heading orientation; and after the participant finished rotation to indicate where an object was located, the target board served as the reset point between trials. The circle on the ground and the target board ensured that the participant's position did not drift during the experiment. From this position, participants completed a memory check - i.e., the objects were occluded, and all participants were asked to turn to each object's location.

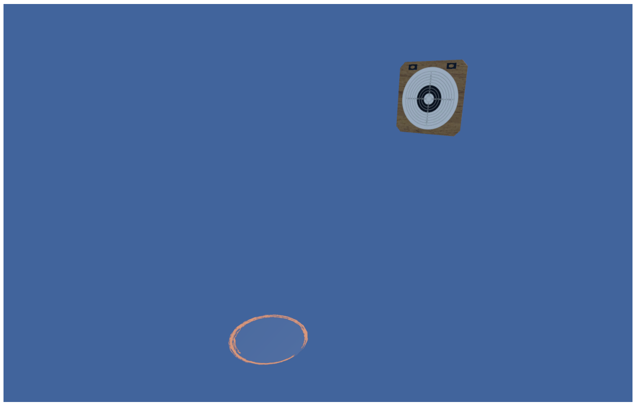

Figure 5: The reset target and position reference from afar

Participants then performed a practice trial and once it was clear that they understood the directions, the experiment began. At the start of each trial, the experimenter told participants to "Look at the [object name]." Participants verbally indicated when they finished turning, at which point the experimenter recorded the turning angle and time. The recorded turning angle was the participant's left and right rotation (yaw) to the target. After each trial, participants were asked to "reset" by turning back to face the target board. Participants were asked to turn to face target object three times each such that 27 trials total were completed per condition. Participants were allowed to refresh their memory between blocks of trials upon request. This made the staircase and objects visible again until the experiment recommenced.

Between each condition, participants completed the Corsi block tapping test [Kessels et al. 2000], a test for measuring spatial working memory, through an online portal.[1] This task involved tapping blocks in the sequence in which they appeared on a computer monitor. If a participant erred on two consecutive trials, then the test ended and the participant was given a score. This task served as a filler task, since the stairwell environments in both conditions were similar, except for the objects.

4 RESULTS

Participants were first instructed to memorize the locations of objects. In both stairwell versions, all participants completed this within 180 seconds. All participants were able to turn to the different object locations in the initial memory check.

The turning error, which was the unsigned difference on the Y-axis between the actual location of the object, and the participant's heading on being instructed to look at that particular object, was measured. Time taken to complete each trial was also measured. We tested for sex differences in both dependent measures, and found no effects so sex was omitted from further analyses.

4.1 Turning Error

Means (and SEs) for the median turning error across all locations are presented in Figure 7

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[1] https://www.psytoolkit.org/experiment-library/experiment_corsi.html

The object that was directly behind participants (on the second landing of the stairwell) in both environments elicited errors at a magnitude ten times that of other errors. Therefore we decided to omit that from the results reported below. Figure 6 shows the corrected mean turning error (and SEs). A repeated measures ANOVA, with mean turning error for each location on the two environments, order of environments (TDH first vs TDV first) and age as a between subjects factor showed only an effect of the error for each location, $F(7, 84) = 7.41, p = .001, \eta_p^2 = .38$. Participants' errors were influenced by the position of the objects, but not by the TDH vs. TEH conditions, order of presentation, or age.

4.2 Latency

Means (and SEs) for the time taken by participants across the trials are presented in Figure 7

A repeated measures ANOVA, with latency for each location on the two environments, order and age as a between subjects factor showed no main effects of order or age, but the interaction of environment and location latency was marginally significant, $F(8, 112) = 2.33, p = .06, \eta_p^2 = .16$. Younger participants were slightly faster than the adults for several locations, and slightly faster in the TEH condition.

4.3 Corsi Scores

All participants completed the Corsi block tapping test through an online portal. The average Corsi score for adults was 5.63 (SE=0.53), and teenagers was 6.50 (SE=0.57). A t-test showed no significant difference between the two age groups, $t(14) = -1.13$, *ns*. Spearman rank correlations revealed no significant correlations between Corsi scores and the dependent measures.

5 DISCUSSION

We began this study by asking two questions: (i) can participants, especially younger participants remember all locations, and (ii) will there be an advantage to having objects distributed by height, i.e., adding the third dimension. Our results have implications for immersive VR as a resource for training and education, and for more specific applications of spatial perception, navigation and orientation used in game development.

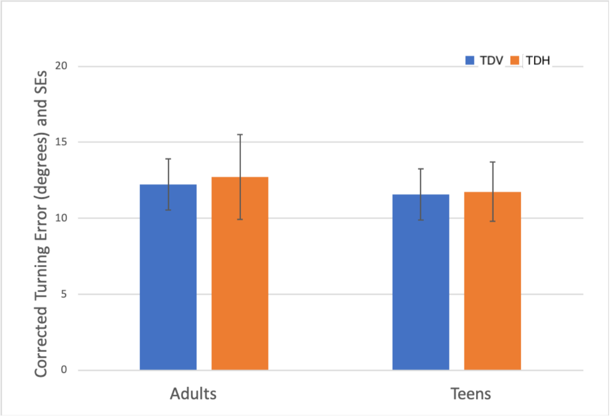

Figure 6: Means (SEs) for Turning Error

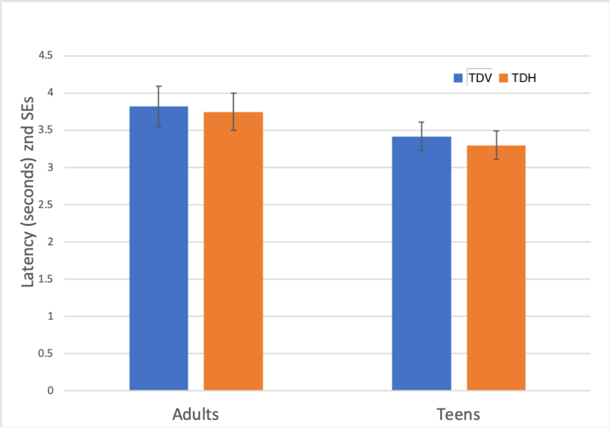

Figure 7: Mean latencies (SEs)

Our results show that participants of both age groups tested here could remember all locations, based on both their low turning errors (< 20 degrees) and low latencies (< 4 seconds). Other studies have shown higher error rates (e.g., Williams et al. [2007]; Narasimham et al. [2018]) albeit in these experiments participants either physically moved to or imagined a different perspective. We observed very few instances when participants hesitated before making a turn, and all but one said they needed no refresher between trials. Regardless of the position of objects in 3D space, both older and younger participants were fairly accurate, a result we would expect from real world studies. Encouragingly, a pattern is beginning to form around VR studies involving teenage children in which children's behavior mimics that of adults. For example, Adams et al. [2018], a motor recalibration study with teenage children found similar effects of motor recalibration as that seen in adult subjects [Mohler et al. 2004; Philbeck et al. 2008; Williams et al. 2006]. Furthermore, Adams et al. [2018] found no age differences between teenagers and younger children on a prism recalibration task in VE. O'Neal and colleagues found that perception-action skills reached adult-like levels by age 14 [Plumert and Kearney 2018]. Given our results and the ease with which 14 year-olds conducted this experiment, future work should test younger cohorts. However, the current lack of robust age differences in this and similar studies may foretell interesting implications for educational and game based applications, and encourages the use of VR for these applications for children. More research is needed to fully understand how age influences perception in virtual reality.

Adding a third dimension did not seem to convey an advantage for aiding recall, but did not pose as a deterrent. Participants' turning errors were not different in the two environments; nor did the order in which they saw the two environments make a difference. There were also no significant differences between older and younger participants, and no significant interactions, except the environment and location. It is interesting that while environment, i.e., TDV or TDH conditions did not matter, specific locations made a difference: some locations were clearly harder and participants were prone to make larger errors than for other locations. A case-in-point is the "chandelier," located in the ceiling in the TDV condition. Participants were most accurate for this location. Outliers were objects such as a sock in the TDV condition, and a shirt in the TDH condition, that were located behind participants and elicited the most errors. Pointing error has been shown to be greater when disparity, the angle of change from learning perspective, increases (e.g., Adamou et al. [2013]; Williams et al. [2007]). Our subjects made modest errors, since disparity was minimal; however this strengthens the argument that errors were not greater because of height changes, and in fact minimized.

Studies in spatial location memory have found differences between males and females (e.g., Eals and Silverman [1994]; Holmes et al. [2015]), or due to age differences (e.g., McGivern et al. [1997]), or due to differences in the task employed such as object location or wayfinding (e.g., Postma et al. [2004]; Schacter and Nadel [1991]). Several studies report no differences in these same factors [Barnfield 1999; Lewin et al. 2001]. We found no differences due to sex. Scores on the Corsi block tapping test, which is a test of spatial working memory, also showed no relationship to our tests of spatial memory. However, this may be due to the smaller sample size (e.g., Kessels et al. [2000]). Our findings were similar to Narasimham et al.'s [2018] in that there were no age differences.

It was interesting that the order in which the environments were presented did not make a difference in both dependent measures. We asked participants which environment they found harder after they finished the experiment. Most participants mentioned the second environment that they saw was harder, but clearly their performance did not corroborate their impressions.

In summary, our results do not reveal significant differences due to adding height as a third dimension for enabling spatial memory, or due to age differences, or due to sex. Perceiving and encoding height as a salient cue may have become a well-honed skill for our participants [Holmes et al. 2015]; that is, when height was available it was encoded, but when it was not, another cue was relied upon, so participants may have performed similarly across both conditions. Further, as Newcombe & Dubas [1992] point out there is an advantage to spatial perception at the onset of puberty, and our youngest participants were above this age. Finally, though many studies have found no difference between real and virtual environments (e.g., [Narasimham et al. 2018; Williams et al. 2007], we need to compare performance in this study to a real-world condition to further understand implications for virtual environments.

6 CONCLUSIONS

In this experiment we used a novel closed staircase VE to study adults' and teenagers' spatial memory for object locations, especially when the objects were distributed across three dimensions vs. two dimensions. Our main findings were that both teenagers and adults were able to memorize locations across three dimensions comparably well as across two dimensions. Our experiment did not reveal age differences in the time for locating objects in the three- vs. two-dimensional stairwells. However object locations influenced both the accuracy and latency. This experiment provides a novel VE, and extends the work of Asjad et al. [2018] as well as evaluating the stairwell environment for spatial memory tasks. Teenagers aged 14-17 were able to use the head-mounted display in a spatial memory task at the same performance level as adults. We plan to continue our studies of age differences in spatial memory, and spatial reasoning with this environment.

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