Investigating the Effects of Display Fidelity of Popular Head-Mounted Displays on Spatial Updating and Learning in Virtual Reality

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Abstract. Often users in VR are required to make mental models, develop spatial awareness, and gain survey knowledge of the environment that they are exploring while learning the content of the simulation. In a between-subjects empirical evaluation, we examined the effect of the display fidelity of popular commercial head-mounted display systems based on display properties such as screen resolution, field of view, and screen size in three conditions, namely low, medium, and high fidelity. Our dependent variables were spatial updating (assessing survey knowledge by measuring the perceived orientation to landmarks previously visited when unseen) and content learning (measured via a pre and post cognitive questionnaire created by domain experts based on Blooms taxonomy of learning). In a VR simulation for geology education, participants explored a terrain, modeled after a segment of the Grand Canyon, collecting and testing rock samples. These landmarks were explored along a winding path through a realistic geological terrain, modeled based on Lidar and photogrammetry data. As the pathway through the Grand Canyon is distinctly sloping and varied, the task of pointing to the perceived location of landmarks in this environment provided rich insights into participants' survey knowledge and content learning, and how such knowledge differed between the display conditions.

Keywords: Spatial updating · Display fidelity · Educational VR.

1 Introduction

Educational VR simulations have been shown to enhance basic knowledge and understanding in fields such as history, science, and engineering, as well as enhance evaluation and creation via 3D interaction with the learning content [5]. Furthermore, these simulations have also been shown to enhance the motor skills

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associated with the task, in essence building muscle memory, potentially due to simulated hands-on interaction, first person perspective, and immersive viewing [2]. In simulated real-world activities, VR has also been shown to enhance students' efficacy and effectiveness in performing the task, as immersion and interaction have been shown to enhance attention to the material and executive functioning [4,17].

In contemporary settings, users have a wide variety of immersive head mounted displays (HMDs) to view learning content. On one hand, there has been an explosion of low cost, easily accessible headsets such as GearVR [9] and Google Cardboard [10] that allows users to leverage their smartphones as the display. Although smartphone VR viewing these days can enable stereoscopic viewing at relatively high resolutions, it may suffer from lower frame rates with complex scenes, lower field of view, and a lack of head position tracking to provide motion parallax. These low fidelity devices are ubiquitous and most learners possess smartphone devices [14]. On the other hand, there have been some recent developments of ultra high resolution (4K pixels per eye) and larger field of view experiences (greater than 150° total horizontal field of view). These high fidelity HMDs, such as the Pimax 8K [18] and StarVR [7], aim to provide close to or near the human visual horizontal field of view. However, the cost of these high fidelity HMDs can be twice as much as other popular commercial models and require advanced graphics cards as well as high end processors to render the scene. These high-end HMDs may not be cost effective for students and may not be as accessible as the low fidelity smartphone based HMD devices. In the middle of the display fidelity spectrum are mid-to-high fidelity HMDs, such as the Oculus Rift [8] and HTC Vive Pro, which may provide an intermediate fidelity of viewing (approximated 110° horizontal field of view) and approximately half the pixel resolution per eye (approximately 2K pixels per eye) to that of the high display fidelity HMDs. Therefore, it is critical in contemporary VR applications to evaluate how the display fidelity of commodity HMDs affects user perception and performance in learners.

A constant in any VR experience is travel in an immersive virtual space, such as those found in numerous VR applications, from factory simulations, field explorations, to educational experiences. When exploring unfamiliar simulated spaces, there is a need to continuously create and update a mental picture or model of the virtual environment [13,27]. As users visually perceive landmarks and features along their path, they update an internal mental representation or model of their surroundings in order to better perform tasks and understand their environment better over time. This process is also a contributing factor in survey knowledge acquisition of the scene explored, and allows users to understand the spatial relationships of objects relative to their present location [12]. This action of updating the mental model of one's surroundings is referred to as spatial updating and is of great importance for the success of many education and training applications in VR [19].

Despite the importance of spatial updating in VR, the effects of display fidelity aspects of visual quality (i.e. screen resolution, field of view, screen size, clarity, and contrast) in commercial contemporary HMDs on spatial updating performance and learning have not been extensively studied. It is important for VR developers, educators, and consumers alike to understand the cost-benefit trade-offs of display fidelity of commercial HMDs on spatial awareness and content learning in educational VR simulations. Our study investigates this need in the literature by empirically evaluating three display fidelity classes of commercial HMD VR systems on a linear continuum from low, mid, to high fidelity and comparing and contrasting their effects on spatial updating and content learning in a geology education simulation.

2 Related Works

The ability for our brain to automatically or continuously create a model of its surroundings during self-motion instead of afterwards through reflection is often referred to as "automatic spatial updating" or "spatial updating" [21]. Though of great importance to the survival of animals, spatial updating in virtual reality is essential for effective training in both educational and entertainment-related tasks.

2.1 Virtual Spatial Updating

Although internal cues were previously thought to be necessary for spatial updating, Riecke et al. [21] showed that visual feedback can be sufficient for perception of self motion. These findings have great implications for virtual reality. As spatial updating is so important in VR, research often focuses on methods to optimize spatial updating performance in VR. Ruddle et al. [22] worked with large-scale virtual environments to determine the optimal travel and rotation metaphors for spatial updating. Their findings indicate that translational body-based information is more important than rotational body-based information for large scaled environments. Riecke et al. [20] compared navigation and search task performance for three conditions, as follows: a) walking, b) physical rotations with a joystick for translations, and c) joystick for both translations and rotations. They found that walking performed the best, but also suggested that methods for experiencing natural rotation in the scene would assist in spatial updating [20]. Weißker et al. [26] investigated the effects of steering compared to teleportation on spatial updating performance. Their findings indicate that steering as a transportation metaphor significantly outperforms teleportation, but at the cost of increased simulator sickness. Cherep et al. [6] similarly researched the effect of travel metaphors on spatial updating. They found that teleportation with head rotation consistently outperformed teleportation without head rotation with regards to spatial updating performance.

2.2 Measuring Spatial Updating

Pointing tasks have become one of the most common methods for evaluating a participant's spatial updating performance [13,15,26]. In these tasks, participants often perform some navigational task that involves both translation and rotation. Periodically, or at the end of the navigation, participants are asked to recall by pointing where they perceive the start or some other landmark that they observed en route. This task often, but not always, takes the form of a triangle completion task where participants move along two legs of a path before pointing to where they perceive the path origin to be [13].

2.3 User Studies on Display Fidelity

In recent years, VR hardware has provided consumers with a variety of improvements in VR, including in the realms of field of view (FoV), resolution, and comfort. As the difference between price points of varying equipment are drastically different, consumers need to know the importance of differing aspects of varying headsets based on their priorities or needs. For example, Young et al.'s research [28] compares two cost-differentiated virtual reality systems. Their work focused on perception and action tasks using the more affordable Oculus Rift versus the much more expensive Nvis SX60. Interestingly, they found that the low-cost system outperformed the high-cost system for perception and action tasks, though at the cost of increased simulator sickness.

The type of trade-offs investigated here and in previous work in contemporary HMD viewing is of great importance to consumers, researchers, and developers alike. Up until now, very little work has been performed in investigating the role of display fidelity of popular commercial head-mounted displays on the differential benefits of spatial updating and content learning in educational VR. Furthermore, as the experiment apparatus in this research utilized a geology education VR simulation that we created with a varied and expansive terrain, the research presented in this paper not only documents spatial updating performance in 2D, but also reports data on spatial updating performance in 3D analyzed using circular statistics in the simulated large scale terrain.

3 Experiment Design

3.1 Research Question

The aim of this study is to investigate the following question: **how does display fidelity of contemporary HMDs differentially affect spatial updating and content learning?** Our hypotheses are as follows:

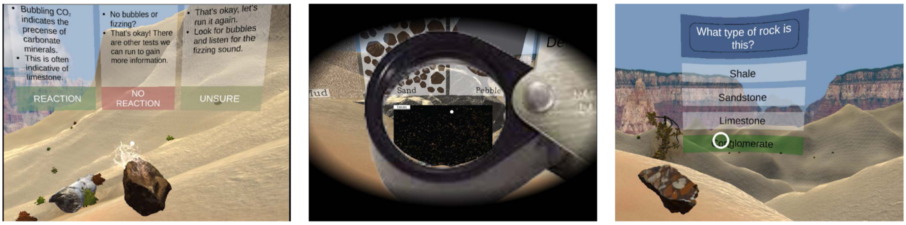
- H1: *Spatial updating performance will be superior in higher fidelity head mounted displays as compared to lower fidelity displays.*
- H2: *Content learning performance will be superior in higher fidelity head mounted displays as compared to lower fidelity displays.*

For this study, the independent variable, display fidelity, will take the form of three varying-fidelity HMD displays: *High Fidelity* (*Hi-Fi* utilizing the Pimax 8K HMD), *Medium Fidelity* (*Mi-Fi* utilizing the HTC Vive Pro), and *Low Fidelity* (*Lo-Fi* utilizing a Gear-VR-like inexpensive plastic head mount with a Samsung Galaxy S9 for viewing). The specifications of these conditions are described in detail in the "Conditions" section.

3.2 Experiment Simulation

Grand Canyon Model: Participants navigated through a model of a section of the Grand Canyon. This model was created using height map data of the actual Grand Canyon near a point of interest called "Hopi Point." This modeling ensured a realistic and accurate representation of the relative topography of the "Hopi Point" area of the Grand Canyon. Part of the texturing of the model included a clear path that participants were instructed to stay on during the whole experiment that also had invisible boundaries preventing them from straying too far. The path was purposely designed so that the spatial updating tests would not be trivial. In other words, the path was not linear in any fashion, but rather had at least one curve between each rock that was tested (see "Rock Tests" below). Furthermore, each rock that needed to be tested had some unique feature in the immediate surrounding environment designed to make that rock memorable and distinct from the others.

Navigation: Movement through the space was implemented using a continuous travel metaphor. Previous studies [26] indicate that spatial updating performance is better using continuous travel rather than teleportation, though at the cost of an increased risk for cybersickness. Participants simply had to press and hold down the designated button on their controller to make their virtual self move forward in the direction that they were facing based on head orientation. For the Lo-Fi condition (Smartphone VR HMD), this was a single button on a Bluetooth controller. For the Mi-Fi and Hi-Fi conditions (Vive Pro and Pimax 8K HMDs, respectively), this was the trigger on the Vive controller. To ensure that participants tested every rock, the user was frozen in place when they came within interaction range of each rock. Participants were allowed to move again once that rock test was completed.



- Bubbling CO_2 indicates the precense of carbonate minerals.
- This is often indicative of limestone.

- No bubbles or fizzing?
- That's okay! There are other tests we can run to gain more information.

- That's okay, let's run it again.
- Look for bubbles and listen for the fizzing sound.

What type of rock is this?

Acid Test Lens Test Rock Identification

Fig. 1. Participants performed multiple geology tests to identify rocks in the environment.

Rock Tests: Participants interacted with nine rocks in the form of 3D models that they came across along their path. The rock tests involved two geological field experiments used to identify the rock. Both experiments had to be completed, though in any order, before the user could identify the rock. One test was the acid test (Fig. 1a) where users determined whether or not the sample reacted with hydrochloric acid, a common indication of a limestone sample. This selection was made based on whether or not visual bubbles and audible fizzing occurred. The other test involved a grain size test (Fig. 1b) where participants looked at the rock under a magnifying hand lens to observe the grain size. After selections were made pertaining to the grain size and acid reactivity of the sample, participants identified the rock (Fig. 1c) using multiple choices with the help of audio hints. The choices included shale, conglomerate, sandstone, or limestone samples. Performing both tests and correctly identifying the rock were necessary for the participant to move on. Requiring participants to test rocks provided an opportunity to improve their geology learning. However, these rock tests also served as a natural distraction task. Distractions in spatial updating tasks can be used as a way to prevent participants from using excessive techniques to improve their spatial updating performance [26]. An example of this would be participants counting steps or time between samples to create a robust mental model of the environment. Furthermore, rock tests served as a way for participants to become familiar with each waypoint by interaction and remembering each rock by name.

Spatial Updating Task: During the course of participants' travel through the Grand Canyon, they were required to complete three spatial updating pointing tasks. These tasks all functioned in an identical fashion. After the participant completed the third rock test in each rock group, they continued on the path until they triggered the spatial updating test. The environment surrounding the participant faded out to gray, and a small stationary square appeared at eye-level. This square served as a reference point; in other words, it provided a reminder to the participant about the direction they were facing when the test began. This reference point was helpful for users to re-calibrate their direction between pointing tasks so that error was not accumulated between pointing tasks. The participant was then prompted to select the location of a certain rock that they had previously tested (or, during some tests, the location of the path origin). A 2D image of this rock and its immediate surrounding environment was shown, along with the rock's name and number indicating the order in which that rock was encountered (i.e., 1–9). Participants were instructed to rotate their head/pointing direction to where they perceived the indicated waypoint to be. When their head was in the orientation they perceived to be correct, they pressed a designated button on the controller to log their head orientation; then, the participant was either presented with another waypoint for another pointing task, or the spatial updating task was ended and the environment faded back in. The reference point square was always visible during these tests, so at any point the participant could turn their head and find the square if re-calibration was desired. In total, 14 pointing tasks were recorded for each participant.

3.3 Participants

Thirty participants, 10 females and 20 males aged 19 to 51, were recruited by use of flyers and word-of-mouth. Ten participants were used for each of the three viewing fidelity conditions, Lo-Fi, Mi-Fi, and Hi-Fi. With three conditions across one-way comparisons as well as 14 measurement repetitions per person, assuming a small to medium effect size of $f = 0.40$ and a correlation of 0.5 between measurements, alpha threshold of $p = 0.05$ and a power of 0.72, we determined a total sample size of 30 (10 per group). All participants were tested to ensure that they did not have any prior domain knowledge in geology and geosciences. Our experiment was conducted using protocols that were approved by the University's Institutional Review Board.

3.4 Conditions

There were three main conditions, *Lo-Fi*, *Mi-Fi*, and *Hi-Fi*. Though 6 degrees of freedom (DoF) tracking is often used with headsets like the HTC Vive Pro or Pimax8K, both of the Mi-Fi and Hi-Fi conditions were limited to 3 DoF (three rotational) in order to match that of the Smartphone condition. The Mi-Fi and Hi-Fi conditions used headsets connected to a desktop with an Intel Core i7-8700 processor and an NVIDIA GeForce RTX 2080 graphics card and were tracked by two HTC Vive base stations. Furthermore, in these two conditions, participants used a single HTC Vive controller for input. The Smartphone condition was characterized by the use of a Samsung Galaxy S9 inserted into a plastic head-mounted display case. Participants in this condition utilized a Bluetooth shutter remote for input. We tried to constrain aspects of the rendering such as scene complexity, level of detail, and refresh rate to be consistent across the viewing fidelity conditions. Please see Table 1 for technical viewing specifications of the condition.

Table 1. Table showing the specs for the three display fidelity conditions in the experiment.

Condition	*Lo-Fi*	*Mi-Fi*	*Hi-Fi*
Hardware	Samsung S9	HTC Vive Pro	Pimax 8K
Total Resolution	2960 × 1440	2880 × 1600	7680 × 2160
Per Eye Resolution	1480 × 1440	1440 × 1600	3840 × 2160
Field of View	80° × 40°	100° × 50°	160° × 60°
Pixels per Inch	570	615	800
Mean Frame Rate	65 Hz	90 Hz	80 Hz

3.5 Methodology and Measurements

Prior to the simulation, participants each took a demographics survey and then the Guilford-Zimmerman Spatial Ability test in order to test that participants across the conditions had similar spatial abilities. During the VR experience, participants completed a total of 14 pointing tasks. For each pointing task, user error was recorded in 3D based on the direction that they perceived the waypoints as compared to their actual direction. Participants also completed a pre and post geology cognition questionnaire in order to assess the learning effects of VR-simulation-based education in the three conditions. The pre and post cognition questionnaire consisted of 15 questions that span the geoscience of the rocks in the Grand Canyon that participants learned via 3D interaction in the VR education simulation. These questionnaires were designed by geologists who are involved in the project and contributed to the design and implementation of the simulation. After the post experiment cognition questionnaire, participants also provided their responses in an object recall list and object placement map, as well as sketching the path that they took in another top-down map of the simulation terrain.

4 Results

4.1 Data Preprocessing

A pre-processing step was necessary since the simple difference between the participants' perceived angle and landmark angle would not be sufficient due to angle wrapping. For example, let's consider a participant's judgements of 5° from the north axis, as compared to an angle of 355° for the perceived landmark direction (with respect to the north axis). If we simply subtract the two, we compute a difference of 350°; however, in reality, the difference is only 10°. To overcome this difficulty, angles can be "wrapped" by adding or subtracting 360, or by employing circular statistics [1,25]. This is a very popular technique in classical perception research on spatial updating and other similar measures that involve a circular quantitative response. We have also analyzed the mean relative error in pointing direction in an absolute angle from the ground truth or actual direction of each landmark as 0°. The analysis of the mean relative error in perceived landmark direction in an absolute angle between the different conditions may reveal any systematic difference in spatial updating by display type overall. The participants' score on the cognition questionnaire was converted to a percentage and was prepared for subsequent data analysis. The two key circular statistics used to ascertain absolute spatial updating performance in our data analysis were: α, the average estimated angle for a particular landmark, and h, the homing coefficient that measures how well the participants' perceived directions "home in" on the actual landmark direction with respect to 3D pointing error. The h value includes information about the accuracy of the perceived direction to the landmark. Please see Turvey et al. [25] for a more detailed explanation of circular statistics. The Grand Canyon terrain that we used as an experiment testbed also has elevation and it would be relevant to examine the participants' spatial updating performance in 3D as a result. The latter analyses also sheds light on how spatial updating in most large scale virtual environments in which terrain elevation is also a factor affects the spatial knowledge acquisition performance of spatial updating.

On all the quantitative spatial updating and learning assessment objective variables, parametric ANOVA analyses were conducted on the data after carefully verifying that the underlying assumptions were met - namely the data in the samples were normally distributed and error variance between samples were equivalent. We ensured that Box's test was not significant. Levene's test was conducted to verify homogeneity of variance, and Mauchly's test of sphericity was conducted to ensure that the error variance in groups of samples were equivalent. Pairwise post-hoc tests between levels of the between-subjects condition variables were conducted using Tukey's HSD analysis.

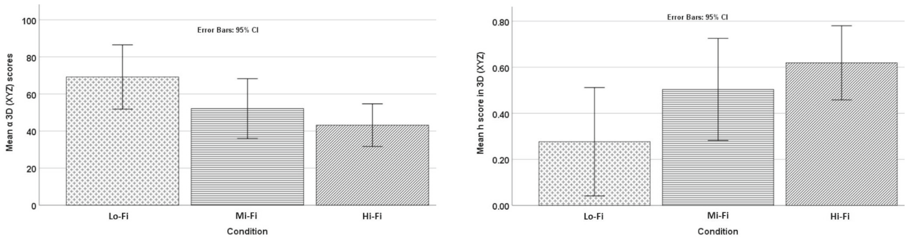
4.2 Spatial Ability Between Conditions

Before comparing the participants' performance between conditions, it is important to examine the influence of any confounding variables. One relevant confounding variable is the participants' innate spatial ability. We collected the participants' spatial ability scores using the GZ test [11]. Analyzing the GZ scores between the conditions via a Kruskal-Wallis H test revealed that there were no significant differences in the GZ scores between the conditions. Overall, when we analyzed the spatial ability variables by gender, we did not find any significant differences by gender in our data set.

4.3 Circular Statistics

Average Estimated Angle to Perceived Location of Landmarks (α.) The α scores in 3D were compared via a one-way independent samples ANOVA analysis. The ANOVA analysis revealed a significant effect of condition, $F(2, 27) = 3.86$, $p = 0.034$ (See Fig. 2 left). Post-hoc pairwise comparisons using Tukey's HSD analysis revealed that participants' average estimated angle to the perceived location of landmarks they examined were significantly lower in the Hi-Fi condition (M = 43.15, SD = 16.09) than the Lo-Fi condition (M = 69.16, SD = 24.24) $p = 0.028$. The popular Mi-Fi condition α scores were in the middle (M = 52.10, SD = 22.58).

Ability of the Participants' Perceived Direction to "Home In" on Landmark Direction. The homing coefficient h scores in 3D were compared via a one-way independent samples ANOVA analysis. The ANOVA analysis revealed a significant effect of condition, $F(2, 27) = 3.58$, $p = 0.042$ (See Fig. 2 right). Post-hoc pairwise comparisons using Tukey's HSD analysis revealed that participants' average estimated angle to the perceived location of landmarks they examined were significantly higher in the Hi-Fi (M = 0.62, SD = 0.22) condition than the Lo-Fi condition (M = 0.27, SD = 0.32) $p = 0.036$. The popular Mi-Fi condition h scores were in the middle (M = 0.50, SD = 0.31).



Average estimated angle α Average "home in" direction

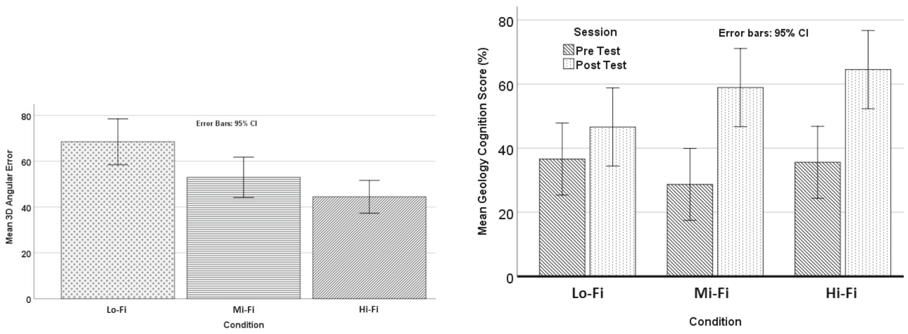
Fig. 2. The average estimated angle α to perceived location of landmarks (left), and the average ability to "home in" on landmark direction (right) in 3D by condition.

4.4 Absolute Angular Error

Absolute 3D Angular Error in Perceived Direction to Landmark Orientation. To place the results in simpler terms, we also calculated the mean absolute value of the 3D angular offsets between the pointing direction and landmark orientation in 3D. We explored the mean absolute angular errors in perceived direction to landmarks by the closest landmarks that they saw, namely the last landmark they saw or 2 landmarks prior or 3 landmarks prior or pointing to the origin, in order to examine if participants perceived the landmark direction more accurately when it was the most recent landmark that they examined. We analyzed the 3D angular error in perceived location in a 3 (between-subjects conditions) x 4 (within-subjects previous landmark visit order) mixed model ANOVA analysis. The ANOVA analysis revealed a significant main effect of condition $F(2,\, 108) = 7.70$, $p = 0.001$, part. $\eta^2 = 0.13$ (Fig. 3 left). The order of previous landmarks visited or the interaction term were not significant. Post-hoc pairwise comparisons using Tukey's HSD analysis revealed that 3D angular errors were significantly higher in the Lo-Fi condition (M = 68.47, SD = 31.38) as compared to the Mi-Fi condition (M = 52.98, SD = 27.48) $p = 0.035$, and the Hi-Fi viewing condition (M = 44.47, SD = 22.42) $p = 0.001$.

4.5 Cognition Questionnaire

The participants' pre and post VR simulation geology cognition scores as a percentage were subjected to a 3(condition) $\times$ 2(session) mixed model ANOVA analysis, after verifying the assumptions of the parametric test. The ANOVA analysis revealed a significant main effect of session $F(1,\, 29) = 49.1$, $p = 0.001$, part. $\eta^2 = 0.65$, and a significant session by condition interaction $F(2,\, 29) = 3.94$, $p = 0.03$, part. $\eta^2 = 0.23$ right. Post-hoc pairwise comparisons using the Bonferroni method revealed that post-test scores (M = 58.90%, SD = 20.55) were significantly higher than the pre-test scores (M = 28.70%, SD = 12.07) in the Mi-Fi condition $p = 0.001$. Post-hoc pairwise comparisons also revealed that post-test scores (M = 64.50%, SD =1 8.18) were significantly higher than the pre-test scores (M = 35.6%, SD = 19.72) in the Hi-Fi condition $p = 0.001$.



Mean 3D angular error

Mean pre and post cognition Scores

Fig. 3. The mean 3D angular error in perceived direction to target by condition (left), and graph showing mean cognition scores as a percentage in the pre and post test session by condition (right).

4.6 Other Variables

Non-parametric statistical analysis on the object recall, object order recall, and path recall scores did not reveal any significant differences by condition. Non-parametric statistical analysis was also conducted separately on the four dimensions of the I-Group presence questionnaire (perceived presence, spatial presence, immersion and realism) [16]. There were no statistically significant differences by condition on these variables. Similarly, non-parametric statistical analysis was also conducted on the system usability scores, gathered via the IBM system usability survey (IBM SUS) [3]. There were no statistically significant differences by condition.

5 Discussion

Our first hypothesis stated that spatial updating performance would be superior in higher display fidelity HMDs as compared to lower fidelity displays. From our spatial updating data analysis, we found highly significant differences to support this hypothesis. Circular statistical values for α, pointing error, were significantly lower for the high-fidelity condition than they were for the low-fidelity viewing condition. Furthermore, h values, homing scores or the ability to home in on a perceived landmark direction, were significantly higher for the high-fidelity viewing condition than they were for the low-fidelity condition. These significant α and h differences held true for pointing values. Though the mid-fidelity condition, with the popular contemporary HMD hardware, scored in the middle for both α and h, there was interestingly no significant differences between the mid-fidelity and the high-fidelity viewing condition, or between the mid-fidelity and the low-fidelity display conditions.

In addition to examining at circular statistics for hypothesis 1, we examined the spatial updating data through the lens of absolute angular error. Similar to the circular statistics data, the high-fidelity display condition contained significantly less pointing error than the low-fidelity display condition. Interestingly, when comparing absolute angular error for the mid-fidelity condition, the mid-fidelity display condition contains significantly more error than the high-fidelity display condition and significantly less error than the low-fidelity display condition.

We also examined the effects of display fidelity on content learning in the geological sciences, as participants had to learn the geology of the rocks they encountered via 3D interactions in the virtual world. In examining how the display fidelity differentially affected learning, we formulated hypothesis 2, which predicted that participants would learn the content more effectively in the high-fidelity display as compared to the low-fidelity display condition. We found that participants learned the task significantly higher in the post-test session, as compared to the pre-test session in both the high-fidelity and mid-fidelity display condition, but not in the low-fidelity condition. Our result indicates that content learning is equivalently effective in popular commercial mid-fidelity as well as high-fidelity viewing HMDs, but not in popular low-fidelity HMD devices.

One of the limitations of our work that we aim to explore in further research is that this study opens up several open questions that are ripe for investigation. The results of our study now opens up further questions such as how FoV and screen resolution of contemporary commodity HMDs can individually affect content learning and spatial updating. Although past research has shown that physically large displays can enhance spatial performance [23,24], as contemporary HMDs evolve in terms of display quality, it becomes crucial to thoroughly evaluate the effects of the innovative display components on user performance and behavior.

6 Conclusion and Future Work

Our data supports the notion that high-fidelity contemporary HMDs allow users to have better spatial updating and content learning than popular lower fidelity displays. This finding should interest developers of VR educational and training applications that take place in expansive and potentially complex virtual environments. Developing an application for a lower or mid-fidelity display will, based on our research, not provide the same experience in terms of spatial updating or survey knowledge acquisition and content learning. Furthermore, consumers of these types of applications could use our findings to justify the need to purchase a popular commercial higher-fidelity device in order to have spatially richer and educationally meaningful experiences. This recommendation also holds true for those in industry applications that use HMDs for training exercises in which spatial knowledge acquisition might be essential. We recommend current visual display hardware designers to continue to invest in advancements in HMDs, since there is evidence that higher-fidelity HMDs are able to provide experiences that lower to mid-fidelity ones cannot. Future work will focus on how factors such as screen size, resolution and field of view specifically in popular contemporary

HMDs contribute to the differences we found on spatial updating and learning performance. We also plan to empirically evaluate how display fidelity affects other measures such as affordances and perception-action coordination.

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