

A Comparative Study of Smartphone, Desktop, and CAVE systems for Visualizing a Math Simulation

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ABSTRACT

We conducted a qualitative study on how users perceive the use of three different systems with different levels of immersion and form factor (CAVE, 3D Desktop and Smartphone) for visualizing a math simulation. Subjective ratings of users' acceptance and immersion experience of the three systems were gathered. We present results from two questionnaires: Technology Acceptance Model and Immersion Experience Questionnaire. The user acceptance of all three systems were rated similarly and highly. However, participants rated their immersion experience of the CAVE and the 3D desktop systems higher than the smartphone. We discuss the pros and cons of using each system.

CCS CONCEPTS

• **H.5.1 Information Interfaces and Presentation: Multimedia Information Systems - Artificial, augmented, and virtual realities;**

KEYWORDS

e-learning, immersion, m-learning, visual thinking, technology acceptance

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1 INTRODUCTION

Over the last few years, researchers and educators have predicted that virtual reality would change the way STEM (Science, technology and Math) are thought. However, widespread adoption has been limited despite the increasing popularity of 3D video games. 3D visualization and interaction may potentially enhance the understanding of complex subjects by learning through observation and interaction. There are numerous systems that can be used to visualize 3D learning simulations. These systems differ in interactivity, navigation, screen size, immersion levels and much more.

The effects of these systematic differences have been studied extensively on learning but there has been little research on how users perceive these systems.

This paper compares three different systems for visualizing and interacting with a 3D math simulation. These systems were CAVE, 3D Desktop and Smartphone. The CAVE is an immersive virtual environment system described in [8]. For the purposes of this study, we define 3D Desktop as a desktop display system with 3D stereoscopic features and head tracking (described as Fishtank VR in [10, 12]). We also define a smartphone as a mobile phone with advanced computing capability and large screen size.

We used a mathematical simulation based on the concept of word problems. The practice of word problems in school mathematics has been argued by some scholars to inhibit applied problem solving (see [31] for a review). This form of learning, which tends to be narrative has been problematic. We suggest that students may benefit from a more visual experience. The capabilities of emerging digital visual technologies may help to extend our visual learning potential [21].

Whereas the CAVE and the 3D desktop has been compared extensively [10, 12], the recent evolution in the 3D capabilities of smartphone technologies is yet to be studied. Mobile phones have been used as an efficient learning tool [29], also referred to as Mobile learning (M-learning). Users are able to access learning materials anytime and anywhere. The growth in support for 3D graphics on smartphones means that we can implement learning simulations that students can potentially access anytime-anywhere. This is one of the motivating factors of this research.

Therefore, our main research question is to explore the subjective opinions of visualizing 3D math simulations using three different systems. The ease of use, usefulness and immersion levels of the smartphone is compared with the extensively researched CAVE and 3D desktop systems. Due to their familiarity with algebraic expressions, staffs and students with teaching/tutoring experience were chosen for the user study.

In the following sections, we review related work and present the implementation of the 3D learning application. This is followed by a description of the user study and interview conducted. Finally, we present discussions of the results, implications for future designs, conclusions and future work.

2 RELATED WORK

2.1 Learning Simulations

3D virtual environments could potentially help learners understand abstractions more quickly. 3D environment can modify learners' conceptual change while retaining much of the complexity of the problems in the real world [25]. 3D environments allow learners to understand dynamic 3D phenomena. This means that 3D environment allows learners to look and walk around easily and

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change their view of the environment. 3D environments can also increase learners' engagement and motivation in the learning tasks while feeling more enjoyable [32]. Errors can be simulated in 3D environments so that learners can learn important lessons. For example, learners can perform a virtual surgery and learn from the consequences of errors. Auditory cues provide very important contributions to the realism of the virtual world, such as the sound of door closing or noise from shoppers at a supermarket. Despite the advantages of 3D virtual environments, constructing one is expensive especially when trying to simulate the fidelity of the real world. There has to be a clear advantage for doing so. Nowadays, with faster developing speed of technology, the equipment is less expensive, and many educational institutions may be able to afford it. However, the question of whether it is worth investing in this teaching method remains. Another drawback is that the learner needs to master the interface and accompanying interaction tools before using the environment. They have to visualize, explore and practice this learning environment before learning can commence.

Recent studies have shown that learning in 3D environment can provide a more effective, motivated way of learning than traditional classroom practices [33]. Roussou et al. [25] investigated user interaction in immersive virtual learning environments and found that the use of a virtual robot provided evidence of conceptual change, where participants revise their conceptions or change their interpretation of something. Their results also suggest that a fully interactive virtual learning environment aided children in solving arithmetical fractions problems. CLEV-R [20] is a desktop and web based multi-user collaborative virtual learning environment. The difficulties associated with developing the 3D application on mobile devices was also discussed. For example, the limitations of screen size and resolution were identified as a barrier to displaying course notes within the VR environment on PDAs. Alice3D [5] is a 3D graphics programming environment designed for undergraduates with no 3D graphics or programming experience. The authors note that middle and high school students were also capable of using Alice to build interactive 3D graphics programs. They also observed that novices had high expectation of the system e.g. subjects often expected collision detection and gravity and were surprised when objects passed through each other or hovered in mid-air.

Several simulations have been studied such as 'Water on Tap' [3] and Virtual Puget Sound [32]. In the 'Water on Tap' [3], subjects were given the task to build a virtual water molecule by creating a virtual oxygen atom and then make correct connection between it and two virtual hydrogen atoms. Interactivity and not immersion was found to be the important factor in learning about atomic and molecular structure. The 'Virtual Puget Sound' [32] was a computer simulation of tidal currents and salinity in Puget Sound, Washington. Results of a user study showed that immersed students had a deeper understanding of the questions posed than non-immersed student, suggesting that immersion helps students construct understanding of dynamic 3D processes. Learning simulations have also been used for mathematics. Math World is a game-based 3D virtual learning environment for second graders [18]. Math world encourages the learners to practice and develop their analytical and problem-solving skills in mathematics by accepting tasks or mission in the form of adventure, quiz and games.

2.2 What influences learning?

It is still very unclear what influences learning. Several studies have debated these influences i.e., interactivity [25], challenge [6], screen size [16], stereoscopy [30], personalized messages [22] and much more. The study of science learning in VEs by Trindade et al. [30] suggests that stereoscopic visualization does not seem to contribute much to conceptual learning, in spite of the sense of immersion provided by the stereoscopic view. Maniar et al. [19] measured the effect of mobile phone screen size on video-based learning. They found that students tended to have a positive overall opinion of M-learning and the videos significantly increased their knowledge of the subject area regardless of screen size. However, they found that learning effectiveness is inhibited if the environment relies heavily on video-based material. Although not related to teaching, Reeves et al. [24] measured the effect of screen size and message content on attention and arousal. They found that screen size, regardless of content, can increase attention and arousal for media messages. However, Bellman et al. found that TV ads were just as effective on PCs and iPods [1] but that viewing angle matters more than screen type. It's not clear whether these results apply to 3D environments.

The concept of immersion is still unclear. See Jennett et al. [15] for a comprehensive discussion. In our study, we study four dimensions of immersion extracted from the study by Jennett et al. (attention, temporal dissociation, interactivity and enjoyment). Attention is one aspect of immersion experience and measures the differences in how much our application drew participants' attention. Temporal dissociation describes the level of presence and awareness of time while participants were experiencing the teaching application. Interaction is the effectiveness of the navigation and manipulation. Enjoyment is the immersion experience that measures how much fun participants had using the application.

The capabilities of emerging digital visual technologies may help in enhancing visual thinking and learning, as highlighted by Mones-Hattal et al. [21]. They argued that visually based curricula need to incorporate an introduction to the use of these technologies in order to enhance human creativity. There are numerous reasons why take-up is quite slow, some of which are also highlighted in our study.

2.3 Visualization Technologies

To our knowledge, this is the first study comparing the effectiveness of the smartphone to a 3D Desktop and CAVE for visualizing a 3D learning simulation. There has been previous research comparing desktop displays with immersive displays (such as CAVE and wall). Swindells et al. [28] evaluated the importance of the physical display environment in the visualization of complex 3D models. They found that individual participants varied widely in their ability to complete their respective tasks, and the display conditions have little influence on task completion and overall completion time. In other words, focusing on display characteristics alone was of lesser importance than other factors such as task structure and improvements in usability of 3D visualization tools [28]. Demiralp et al. [10] and Prabhat et al. [12] compared the CAVE and fishtank displays with different results. The former found that users performed an abstract visual search task significantly more quickly and more accurately on the fishtank VR display system than the CAVE. The

latter found the opposite results. Prabhat et al. suggested that these differences may have been due to a number of factors, notably the subjective feedback approach used by Demiralp et al.

A desktop environment has some obvious advantages compared with CAVE, as it does not require participants to distribute their attention over a very wide area of visual space. However, we cannot simply imply that large and immersive devices are totally inappropriate for 3D visual experience. When there is a scenario that requires several people to work together, the large-scale screen of CAVE allows each person to work on their own job and more easily to share the same display space, which cannot be simply achieved by desktop. CAVE allows simple navigation metaphors for local movement, as the participants can just move around an object.

The pervasiveness and improvement in performance of smartphones could potentially change how we use them for learning. A study of M-learning on hundreds of Japanese students [29] demonstrated the acceptance of mobile phone for learning and optimism about its potential for learning. Although the smartphone is still generally used for video-based learning [19], the 3D potential is also enormous. Indeed, Falaki et al. [11] found that high school students use communication and games applications more on smartphones. They also found that interactions with maps and games tend to be the longest. Chehimi et al. [4] highlights the gaming possibilities on mobile phones. Recent smartphone sensors, such as the accelerometer, present an opportunity for new interaction mechanisms. However, this potential is tempered by the difficulty of developing on mobiles. Lane et al. [17] presents a survey and open challenges in the emerging field of mobile phone sensing.

Clearly, it's still relatively unclear how the smartphone would be evaluated relative to the 3D desktop and CAVE for visualizing a 3D learning simulation. Therefore, our research effort is concerned with subjective comparisons of these three visualization systems for enhancing the learning experience. Acceptance and adoption of the innovative use of smartphone has been investigated in many industries e.g., health [23]. Smartphone adoption in education deserves investigation in its own right. This study contributes to the field by adding an important new investigation i.e., the perceived adoption of smartphones for visualizing 3D math simulations.

3 MATERIALS

3.1 Application Design

In our application, we developed a 3D math simulation in the Unity3D game engine [7]. We deployed it to the CAVE, 3D Desktop and Smartphone after programming the input modes for each interaction accordingly (see below). We used the *word problems* [31] approach for mathematical simulation. This is based on the premise that providing a visual aspect to the concept of wording mathematical problems may help to improve learning. However, this study does not study if there were any effects on learning. We focus on comparing subjective evaluations of the technology acceptance and immersion levels of three different systems.

In the simulation, a narrator read out a script explaining the topic of “collecting like terms”. A section of the script reads as follows:

“Tom has a fruit shop and he only sells apples, bananas and coconuts. Bob comes and buys 3 apples. But how can we revise it down. We let 'a' represent apple, 'b'

represent banana and 'c' represent coconut. Then we can say that Bob has '3a'. And we know '3a' as 3 apples. If Bob buys another apple, then we can tell that Bob has '3a + a = 4a'. Sue comes to buy 2 apples and 4 bananas. We can write this in algebra which is '2a + 4b'. Terry comes and wants 6 apples, 3 bananas and 5 coconuts. Then we can write this in algebra as '6a + 3b + 5c'. Andy is also a customer who is always not sure what to buy. So, he buys first one apple, one banana and one coconut, and then he wants three more apples, five more bananas, one more coconut and another coconut. Then we can say that Andy has 'a + b + c + 3a + 5b + c + c = 4a + 6b + 3c' by grouping the letters together. We can also do the subtraction. Another day, Andy comes to buy 2 apples and 5 coconuts, and then he returns a coconut. Then Andy has '2a + 5c - c = 2a + 4c' ...”. It ended with: “Try some other combinations yourself and see what you get”.

The appropriate items were animated accordingly, as the storyline was being narrated. During the interaction phase of the CAVE and desktop, the position of a white-coloured cube provided instant feedback for picking up items within the environment.

3.2 System Details

Three systems were utilized for visualizing the interactive 3D mathematical application (Table 1).

3.2.1 Immersive Projection Technologies (CAVE-like Display). The application was run in a four-wall CAVE system (Figure 1(a)) with participants wearing an Intersense IS-900 head tracker situated on a CrystalEyes stereo shutter glasses. The front, left and right walls are back-projected acrylic screens with dimensions of 3m x 2.2m while the 3m x 3m floor was projected from above. Each wall was driven by a PC with NVIDIA QuadroFX 5600 graphics card. The screens have a dimension of 3m x 2.5m and were stereo projected by Christie Mirage DS+6K-M projectors with a resolution of 1400 x 1050 and a refresh rate of 100Hz. In addition to the near-surround visual display, 8 speakers (one at each corner of the cube) plus a separate sub-woofer provide spatialized sound. Interaction with the environment was achieved using a hand tracker with built-in joystick and buttons connected to the white cube. The joystick controlled the position and orientation while the button was used for picking up.

3.2.2 3D Desktop Display. The application was run on a desktop computer (Figure 1(b)) with Windows 10, Intel Quad-Core i7 2.79GHz CPU and 3.25GB RAM. For the stereoscopy with head tracking, we used the Nvidia GeForce 3D Vision Kit, which includes a pair of wireless 3D glasses and an Infrared Emitter connected to the desktop via USB 2.0. The display was run a 22” Samsung SyncMaster 2233RZ 120Hz monitor with a resolution of 1024 x 768 (full-screen mode) driven by a NVIDIA GeForce GTX 260 graphics card. Participants in this group wore a stereo headphone. Interaction with the environment was achieved using a mouse and keyboard. The mouse controlled the main camera's position and orientation while the keyboard was connected to the white cube for picking up items.

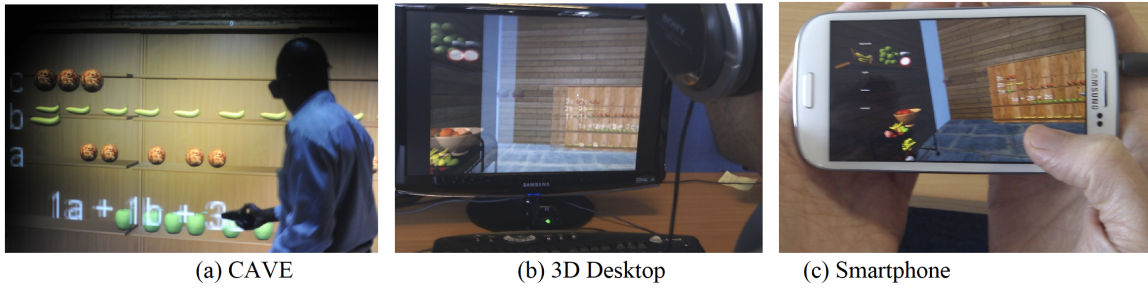


Figure 1: CAVE, 3D Desktop, and Smartphone Virtual Environments used in the studies.

Table 1: Features of the three systems

	CAVE	3D Desktop	Smartphone
Stereoscopy	Yes	Yes	No
Head Tracking	Yes	Yes	No
Screen Resolution	1400 x 1050	1024 x 768	1920 x 1080
Display Dimensions	3000mm x 2200mm	558.8mm wide	113mm x 630mm
Navigation and Selection	Hand tracker (built-in joystick & buttons)	Mouse Keyboard	Accelerometer Touchscreen

3.2.3 Smartphone. The application was run on a Samsung S5 smartphone (Figure 1(c)) with Android OS version 6.0, Quad-core 2.5 GHz CPU and 2GB RAM. The smartphone features a HD Display with dimensions of 113mm x 630mm and a 1920 x 1080 screen resolution. Participants in this group also wore a stereo headphone. Interaction with the environment was achieved using the built-in accelerometer and touchscreen functionalities. The accelerometer readings controlled the orientation of the main camera. We applied low pass filtering on the accelerometer readings to smooth it and get rid of high frequency noise. The swipe function of the touchscreen controlled the main camera’s position and orientation while the tap-screen function was used for picking up. Preset screen positions determine the item that was picked up.

4 USER STUDY

4.1 Method

4.1.1 Participants. Thirty-six unpaid participants (22 males and 14 females) made up of staffs and students volunteered to take part in the study. All participants had normal or corrected-to-normal vision and no color blindness. Ages ranged from 19 to 50, with a mean of 26 and a median of 24. All participants were required to have prior knowledge of algebra. All participants had varying teaching or tutoring experience (secondary school, university and personal tutoring).

4.1.2 Design. Participants were randomly divided into three groups (between-subjects), hence experienced only one of three systems (CAVE, 3D Desktop and Smartphone). An additional within-subjects questionnaire factor enabled the analysis of participants’ subjective ratings.

4.1.3 Procedure. Participants were told that they were going to watch a simulation about algebra for three minutes. While the simulation was still playing, they were able to adjust the position and orientation of the viewpoint as they wished. After the narrator finishes explaining the mathematical topic, they were able to pick up objects in the scene by picking up items using the available input mechanism built into the system they were assigned. They got instant visual feedback on how like terms are collected. Participants could pick up any fruit they wanted on the shelf. The concept of this interaction is that the same kinds of fruit are added together, hence enabling users to understand what terms you can add together and which you cannot. This is referred to as: “collecting like terms” in algebra. After each experiment, participants were asked to fill out the questionnaire, which included items on their assessment of the degree of technology acceptance and immersion experience.

4.1.4 Measures. To measure the relationship between user and a system, we cannot simply rely on any invalidated subjective measurement. Therefore, questionnaire data was collected using the Technology Acceptance Model (TAM) [9] and a shortened version of the Immersion Experience Questionnaire (IEQ) [15]. Participants also completed three questions on their perception of technology in order to check for variability in participants’ perception, which may influence their opinions.

The user acceptance of technology was measured by the technology acceptance model that consists of two fundamental determinants of system use: perceived usefulness (6 questions) and perceived ease of use (6 questions) [9]. Perceived usefulness measures how users tend to use or not use a system to the extent that they believe it will help them perform a task better. With perceived ease of use, users may believe that a given system is useful, however, at the same time they may still feel that the system is too hard to use

or learn and that the performance benefits of usage are outweighed by the effort of using the application. We can just refer this as “the degree to which a person believes that using a particular system would be free of effort”. It has been shown that this model can also be used to evaluate M-learning [14]. Cronbach’s alpha α for the perceived usefulness was 0.922 and the perceived ease of use was 0.879, suggesting that the ratings have relatively high internal consistency. Participants judged the acceptance ratings on a seven-point Likert scale ranging from 1 (unlikely) to 7 (likely).

To measure the immersion level of the CAVE, 3D desktop and smartphone, we used selected questions of the immersion experience questionnaire [15] consisting of four dimensions: attention (Q1 - Q4), temporal dissociation (Q5, Q6), interactivity (Q11, Q15) and enjoyment (Q28 - Q31). Cronbach’s alpha α was 0.80, suggesting that the ratings have relatively high internal consistency. Participants judged the IEQ on a five-point Likert scale ranging from 1 (Not at all) to 5 (A lot/Very much so).

4.2 Results

4.2.1 Perceptions of Technology. The mean responses of the perceptions of technology were rated on a five-point Likert scale ranging from 1 (Not at all) to 5 (A lot) and tabulated. The dependent variable data were entered into a one-way ANOVA with one factor: Technology (CAVE, Desktop, Smartphone).

There was no significant main effect of technology, $F_{(2,33)} = 0.147$, $p > 0.05$. The mean responses were CAVE (3.972), Desktop (4.111), Smartphone (4.028). The homogeneity of variance was not significant, $p > .05$, which showed that the error variance of the dependent variable is equal across the groups, hence the assumption of the ANOVA test has been met. Post-hoc Tukey tests also revealed no significant differences between participants’ perception of technology for all pairs.

4.2.2 Technology Acceptance Model. The mean ratings of the Technology Acceptance Model were tabulated. The dependent variable data (acceptance ratings) were entered into a 3 x 2 mixed design Analysis of Variance (ANOVA) with two factors: technology (CAVE, 3D Desktop, Smartphone) and TAM (perceived usefulness, perceived ease of use).

There was no significant main effect of technology, $F_{(2,33)} = 1.126$, $p > 0.05$ with similar mean acceptance ratings for the CAVE (Mean, $M = 5.750$), Desktop ($M = 5.410$) and Smartphone ($M = 5.160$). Post-hoc Tukey tests also revealed no significant differences between participants’ technology acceptance ratings for all pairs. See Figure 2

We employed Mauchly’s test of sphericity to validate our repeated measures factor ANOVAs, thus ensuring that variances of differences are not significantly different. As the repeated measures factor (TAM) had only two levels, the sphericity assumption was met. The main effect of TAM was significant ($F_{(1,33)} = 12.282$, $p = 0.001$), with higher levels of acceptance ratings for perceived ease of use ($M = 5.630$) than perceived usefulness ($M = 5.250$). There was no significant interaction effect between the technology and TAM, $F_{(2,33)} = 0.177$, $p > 0.05$. Participants’ acceptance rating did not significantly differ between all pairs of technology for either the perceived usefulness or ease of use. However, closer scrutiny revealed the cause of the significant main effect of the TAM. The

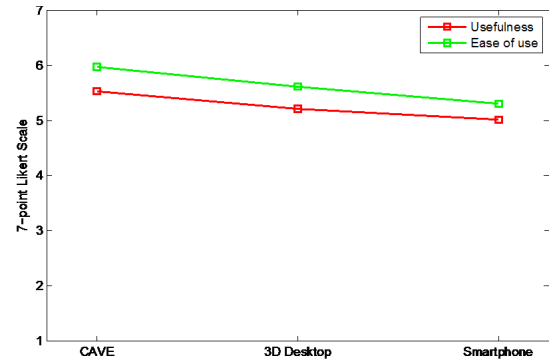


Figure 2: Participants’ subjective ratings of the Technology Acceptance Model.

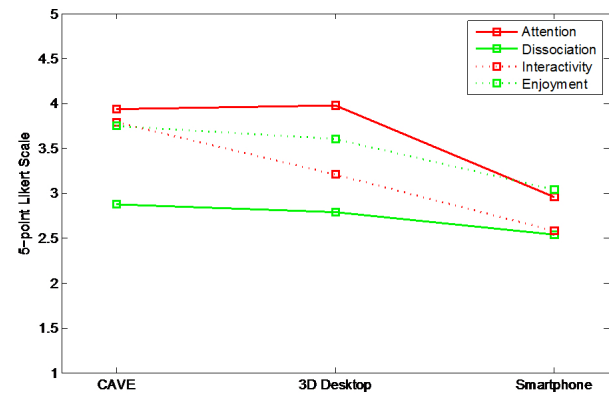


Figure 3: Participants’ subjective ratings of the Immersion Experience Questionnaire.

perceived ease of use of the CAVE, $p < 0.05$ and the desktop, $p < 0.05$ were rated higher than their perceived usefulness. The differences for the smartphone were not statistically significantly, $p = 0.130$.

4.2.3 Immersion Experience Questionnaire. The mean ratings of the Immersion Experience Questionnaire were tabulated. The dependent variable data (immersion ratings) were entered into a 3 x 4 mixed design Analysis of Variance (ANOVA) with two factors: technology (CAVE, Desktop, Smartphone) and IEQ (Attention, Dissociation, Interactivity, Enjoyment).

There was a significant main effect of technology, $F_{(2,33)} = 9.791$, $p < 0.001$. Post-hoc Tukey tests revealed that immersion ratings for the CAVE (Mean, $M = 3.589$) was not significantly different from the desktop ($M = 3.396$), $p > 0.05$. However, the smartphone’s immersion ratings ($M = 2.781$) were significantly lower than the ratings of either the CAVE or desktop.

Mauchly’s test on the IEQ factor indicated that the assumption of sphericity had been violated ($\chi^2 = 19.994$, $p < 0.05$), therefore degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\epsilon = 0.691$). The results show that the main effect of the IEQ was significant ($F_{(2.07,68.42)} = 12.812$, $p < 0.001$).

There was no significant interaction effect between the technology and IEQ, $F_{(4.15,68.42)} = 1.485$, $p > 0.05$. Paired comparisons

of the technologies for each dimension of the IEQ revealed that the smartphone's immersion ratings significantly differed from the CAVE and desktop for the attention, interactivity and enjoyment. However, participants' immersion ratings did not significantly differ between all pairs of technology for the temporal dissociation. See Figure 3

5 GENERAL DISCUSSIONS

The main findings of this study are:

- Participants' acceptance of smartphone, CAVE and 3D desktop technologies for visualizing math simulation was not significantly different.
- Participants' assessment of the immersion experience of the smartphone was significantly lower than the CAVE and 3D desktop.
- An analysis of a possible confounding influence (perceptions of technology) revealed no significant differences between the systems, confirming that participants did not have significantly different perception of technology that would influence their subjective assessments of the systems.

5.1 Technology Acceptance

The difference between subjective ratings of the TAM for the three systems were not significant (Figure 2), demonstrating that all three systems were accepted quite well for visualizing the math simulation. A possible explanation for this phenomenon is that the desktop and smartphone are mature technologies. Participants would not have too much difficulty with usability and interaction. On the other hand, the CAVE is a system that is not widely used, and users have to become familiar with the interface of the system. The natural intuitive interface of the CAVE makes it easy to use. Hence, participants felt that such a system should also help users to achieve their tasks more effectively and efficiently, once they've quickly overcome the learning curve. The fact that CAVE gets the highest rating among the three systems supports this viewpoint.

5.2 Immersion Experience

We need to discuss our finding that the smartphone's immersion ratings were significantly lower than the CAVE and desktop for the attention, interactivity and enjoyment, while the temporal dissociation did not differ. Figure 3 shows the differences between the four dimensions of the immersion experience that we studied.

5.2.1 Attention. We suggest that the influence of the stereoscopy and head tracking of the CAVE and 3D desktop may have had an effect. This is in line with the finding by Schild et al. [26] that more attention is allocated to stereoscopic 3D games than monoscopic ones. The touchscreen interface of the smartphone may require more time in the learning curve than was afforded to the participants, whereas the natural control of the CAVE and the ubiquity of a desktop interface may have played a major part in holding people's attention. The novelty factor of the CAVE is also a potential factor, as highlighted in the group interview.

5.2.2 Temporal Dissociation. The temporal dissociation asked users about the extent to which they lost track of time. Ratings for the CAVE, 3D desktop and smartphone were rated similarly.

It should be noted that the overall rating is relatively low for all systems. This is likely due to the complexity of the task, as the focus of our task was on exploration.

5.2.3 Interactivity. The interactivity scores of the CAVE and 3D desktop were higher than the smartphone. The CAVE uses a hand tracker (with built-in joystick and buttons), stereoscopic screens and head tracking. The 3D desktop uses a stereoscopic monitor, mouse, keyboard, head tracking. The smartphone uses the built-in accelerometer and touchscreen. The ability to freely move around the CAVE and experience the environment firsthand and from multiple viewpoints gives participants a feeling of natural control. The ubiquity of the desktop coupled with the stereoscopic effect also gave the 3D desktop an edge. However, the lack of familiarity with the use of smartphones for 3D games may have had a negative impact on participants' perception of the smartphone's interactivity. Chehimi et al. [4] highlighted the challenge of developing on smartphones. The touchscreen functionality is the main way of navigation and selection in a 3D environment. This tends to mean that the learning curve associated with using the smartphone is not steep (gradual). Although, the application was programmed to avoid sudden rotations due to minor hand movement, it still felt like an unnatural way of navigating 3D environments, as they had to adapt their normal hand behaviour.

5.2.4 Enjoyment. The enjoyment ratings for the CAVE and 3D desktop were significantly higher than the smartphone. The natural feel of the CAVE seems to give participants a sense of fun. The desktop was also rated highly in this respect. The questions posed on participants' level of enjoyment included graphics and imagery, intention to use and feeling of disappointment when it was over. This is despite the fact that the resolution of the smartphone was higher than the desktop. The lower performance of the smartphone may be an indication that screen size may have had an effect.

5.2.5 Perceived Usefulness. In our results, participants perceived the smartphone as very useful because they could foresee the potential of the smartphone for 3D applications. Previous study by Huang et al. [14] investigated users' acceptance of M-learning and found that perceived usefulness affects individuals' attitudes more than perceived ease of use. They also found that the more a user appreciates the value of mobility, the more the user will perceive that M-learning is useful. They suggested that designers should endeavor to maximize the usefulness of M-learning.

5.3 Summary

The results showed that 3D desktops are just as suitable for visualizing simulations as the CAVE. We also believe that the 3D desktop is more likely to engage students over the long-term.

Despite the immersion results, the potential of smartphones for visualizing 3d learning applications is appealing. Today's smartphones come with a growing set of embedded sensors [17], such as an accelerometer, digital compass, gyroscope, GPS, microphone and Time of Flight cameras, which can be utilized by 3D applications. More work needs to be done on how we would leverage the new functionalities to improve 3D interaction on this medium.

6 CONCLUSIONS AND FUTURE WORK

The aim of this project was to explore the differences between the CAVE, 3D desktop and smartphone systems for visualizing an interactive 3D math simulation. A review of previous work highlighted the differences in findings by various studies. The subjective ratings of the CAVE, 3D desktop and the smartphone demonstrated their ease of use and usefulness. The CAVE and the 3D desktop were rated higher than the smartphone in terms of capturing users' attention, level of interactivity and a stronger feeling of enjoyment.

We have conducted a focus group interview of teachers who were familiar with teaching math and are currently working on analyzing and integrating the findings within the systems. Future work will concentrate on the collaborative use of learning simulations using the different visualization systems we've explored. We also intend to deploy an improved version of the application to the tablet computer. More work is needed to compare the effectiveness of tablet computers with smartphones. Future work will also concentrate on quantifying the learning effectiveness of these systems on young students in school environments. Although the choice of application here was a mathematical topic, applications can be developed to enhance visual learning in many other subject areas (notably science) for use on the devices we studied.

In a traditional educational setting, communication between learners and teachers are face to face. With this form of learning, groups of learners can share the same virtual environment synchronously or asynchronously. They can either be co-present or remotely located. A learner with a smartphone could communicate with one on the desktop, or vice versa. 3D environments could potentially allow the teacher to visualize a problem for the learner.

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