Conceptual Learning and Immersive Properties in Head-Mounted-Display Virtual Reality Simulations

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Introduction

Immersive Technology in Education

The rise in mainstream adoption of head-mounted-display (HMD) virtual reality (VR) platforms in the past decade has brought about the potential for educators to use increasingly immersive technologies. In the context of this research, the term 'immersion' can be used to describe the degree of involvement a user experiences in a simulation (Cheng, et al., 2015a). Immersion may be increased by using HMD VR simulations instead of desktop-based VR simulations (Mania, K., 2001). Immersion may also be further enhanced in a HMD VR simulation through inclusion of additional immersive properties, such as those which increase a simulation's sensory realism or invoke user empathy with a virtual environment (Slater & Wilbur, 1997; Brown & Cairns, 2004).

The efficacy of immersion to produce enhanced learning outcomes in the context of HMD VR, has been studied for decades (Witmer & Singer, 1998). Previous studies have outlined the positive effect that increased immersion can have on task performance within a virtual environment (Welch, 1999; Witmer & Singer, 1998; Ragan, et al., 2010; Cheng, et al., 2015a). For example, research has found a positive correlation between users' perception of their own level of immersion and measured spatial understanding in HMD virtual environments (Oprean, et al., 2015; Stanney, et al., 2013). A similarly positive correlation has been observed between immersion and users' measured memory recall (Mania, 2001).

Despite the potential benefits, implementing or enhancing immersive properties in a virtual environment can have disadvantages. In addition to heightened cost due to increased time of development (Bayarri, et al., 1996), increased immersive properties may be a potential distraction to users, leading to cognitive overload (Makransky et al., 2019). Understanding the trade-offs involved in increasing immersion is an important design consideration for educators and developers using VR to support students' learning.

How Immersive Properties Can Influence Learning

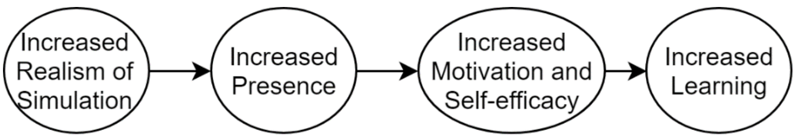

Figure 1: Relationship between simulation realism and learning (adopted from Makransky & Peterson (2019), Figure 3)

A framework (based on structural equation modelling) which describes the process by which immersive properties may evoke psychological responses from users was described by Makransky & Peterson (2019). The study identified two paths between levels of immersion and perceived learning outcomes. The two paths were referred to as the affective and cognitive paths. The path most relevant to the current study is the affective path; specifically, the path that stems from representational fidelity (Figure 1). Makransky & Peterson (2019) define representational fidelity as the degree of realism of the virtual environment (i.e. the extent to which the virtual environment is realistic).

Figure 1 shows that the degree of realism in a simulation was related to the users' perceived presence or "being there" in the virtual environment (Makransky & Peterson, 2019). A user's level of presence in turn influenced their motivation and self-efficacy. An increase in self-efficacy was found to have a positive influence on their learning.

Immersive Properties and Conceptual Learning

Conceptual learning has been described as a person's cognitive process when making sense of a learning concept (Whitelock, et al. 1996). Some studies have suggested potential for a link between immersion and enhanced conceptual learning (Schiefele, 2001; Witmer & Singer, 1998). However, empirical evidence suggesting this effect is scarce. An example of a study which attempted to explore this effect was a study conducted in Taiwan (Cheng, et al., 2015b). This study tested the relationship between immersion and conceptual learning, but found no clear relationship. One explanation given for this was that participants were unable to reach high levels of immersion with the tested simulation because the simulation was desktop-based and contained few immersive properties.

The current study explored the relationship between immersion and conceptual learning in the context of a HMD virtual reality simulation. The study asked:

What is the relationship between conceptual learning and the use of immersive properties in head-mounted-display virtual reality simulations?

Method

Research Design

A qualitative research design was adopted. Using a strategy informed by Usoh, et al. (1999), two versions of the same simulation were developed. Each simulation was designed to support either low or high immersion achieved through embedding less or more immersive properties, respectively. Participants engaged with both versions of the simulation and subsequently responded to the questions shown in Table 1 while reflecting on their experience. Participants' responses were subsequently analysed to answer the research question.

Table 1: Post workshop questionnaire

Question
1. Which module (if any) do you believe has the strongest potential to help the "player" improve their ability to relate piping and instrumentation schematics to three-dimensional systems?
2. Having completed the simulations, do you feel confident that you could translate any new-found knowledge to a real-life workplace scenario? Explain. If a particular simulation was most helpful in generating this confidence, please identify which one and explain why this is the case.
3. Which module's auditory and visual environment did you feel distracted you the most from completing the assigned task (if any)?

Question 1 explored participants' preference between the two simulations based on the comparative support to develop learning outcomes. Question 2 investigated whether the realism of the high immersion simulation resulted in any perceived increase in self-efficacy related to the learning outcomes. Finally, Question 3 of the questionnaire explored any immersive properties that may have had an adverse effect on participants' experience when completing the high immersion simulation. Participant responses offer insights into the perceived psychological reactions of users to the intended immersive properties.

Participants

Eighteen students at a research intensive university in Australia attended a workshop. This workshop was offered over the course of a day and involved 18 overlapping sessions. Students were recruited via an email to all engineering students at the university. Of the 18 participants, 11 were male and 7 were female. Participants were from the following engineering disciplines: Electrical - 6; Civil - 4; Chemical - 3; Biomedical – 2; Environmental – 2; Software – 1; Mechanical – 1. Eleven students were enrolled in undergraduate programs, while seven were enrolled in postgraduate programs. Five participants had previous experience with piping and instrumentation diagrams. Five participants had previous experience using HMD simulations. Upon completion, students received a $25 dollar voucher for the campus academic supply store, as well as one hour of time credited towards engineering work experience. The study received ethics approval from the institution's Human Research Ethics Committee.

Workshop Procedure

Workshops were conducted for one hour per participant which provided time for the demographic questionnaire, two simulations, and a qualitative evaluation survey. First, participants completed a demographic questionnaire. The workshop facilitator then provided participants with a tutorial on using the HTC Vive™ including an explanation of how to complete the simulated task. Participants then completed the two simulations. One half of the students completed the low immersion simulation first, and the other half completed the high immersion simulation first. While participants completed the simulations, notes were taken by the facilitator to record participant behaviour that was not likely to be self-reported in the evaluation survey.

Simulation Design

The simulations were developed using the Unity™ engine (Unity 2018). The simulations were designed to be used by a HTC Vive, which included a motion-tracked HMD with two motion-tracked controllers.

The simulations took place in the context of a typical task for a mechanical engineer. In this task, participants were placed in a virtual factory room with a hot water fluid system positioned against a wall. The player-character was provided with a clipboard in the simulation which was controlled using one of the two HTC Vive controllers. Attached to the clipboard was a sheet of paper including a piping and instrumentation diagram which detailed the schematics of the fluid system. The user was given the task of linking specific components of the piping and instrumentation diagram with their respective components on the 3D model. The user was able to do this in the simulation by placing their second controller near the correct component and holding down the trigger on the back of the controller.

The immersive properties explored in the current study were taken from two sources. The first source (Slater & Wilbur, 1997) recognised a set of technological immersive properties of a virtual environment. The properties that were utilised by the current study were those that make a virtual environment 'inclusive', 'extensive', and 'vivid' (pp.603-604). Respectively, these refer to the: extent to which physical reality is shut out; extent to which the virtual environment stimulates one's senses; graphical fidelity and detail. The second source (Brown & Cairns, 2004) recognised a set of emotional immersive properties of a virtual environment. The two that were utilised by the current study were 'empathy' and 'atmosphere' (p.1299). 'Empathy' describes the attachment the user feels towards the virtual environment while 'atmosphere' describes the effect of the environment directly reacting to the actions and location of the player-character.

A significant disparity in immersion between the two simulations was achieved by implementing these immersive properties in the high immersion simulation (Figure 2), but not in the low immersion simulation (Figure 3).

Figure 2: High-Immersion Simulation

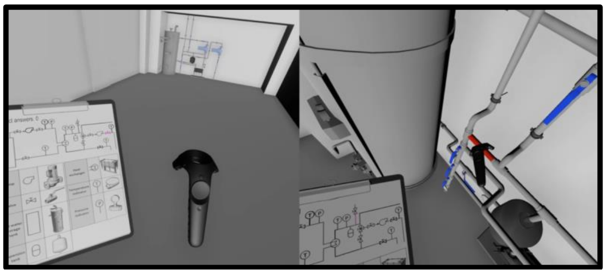

Figure 3: Low-Immersion Simulation

The 'inclusive' property was achieved by the use of headphones, whereby auditory isolation separated the user from the surrounding environment. The 'extensive' property was accomplished by introducing auditory and haptic elements to the simulation. Audio cues included atmospheric sounds from the environment as well as story-based dialogue. Haptic feedback came in the form of vibration when selecting components. The 'vivid' property was realized by introducing realistic textures, shadows, and lighting. 'Empathy' was created through telephone dialogue from an engineering manager which was heard by the user at the start of the simulation, detailing a back-story of the context in which player-character had been given the task. Finally, 'atmosphere' was achieved with the use of dynamic audio from the pumps, which varied in volume depending on the player-character's position and orientation.

Results

Qualitative Survey

Of 10 participants who responded to the first part of question 1, 8 participants reported that the high immersion simulation was more effective, and 2 participants reported that the low immersion simulation was more effective. Some explanations for the first response were "[The high immersion simulation] was more realistic and aided my learning", "[The low immersion simulation] is boring", "The audio in [the high immersion simulation] made it feel like someone was guiding me" and "[The high immersion simulation] was authentic while [the low immersion simulation] was inauthentic and therefore was forgettable". Two participants who gave the second response both noted that the low immersion simulation (which did not utilise audio) was superior because they could talk to the workshop facilitator when they needed help.

All 16 participants who answered the first part of question 2, answered "Yes". Eight participants answered the second part of this question and all stated that the high immersion simulation was most helpful. Five of the eight participants explained this answer by declaring "[The high immersion simulation] was more like a real workplace".

Of the 12 participants who answered question 3, four participants reported that the low immersion simulation was most distracting, and two reported that the high immersion simulation was most distracting, and six reported "neither". A common explanation for the first response was "The audio in [the high immersion simulation] blocked out distractions from the real world". One participant's explanation for the second response was "The audio in [the high immersion simulation] distracted me".

Facilitator Notes

The facilitator noted that participants without prior experience with HMD VR struggled with correct use of the teleportation mechanism which allowed the player-character to move around the virtual environment.

It was also noted that some participants who had issues with the simulation frequently asked the facilitator for help, often having to remove their headphones during the high immersion simulation. Further, the facilitator observed that many participants completing the high immersion simulation did not wait until the initial dialogue was complete before starting the task. The dialogue seemed to distract participants and was often a reason why participants seemed compelled to remove their headphones before communicating with the facilitator.

Discussion and Implications

Overall, participants were in favour of the high immersion simulation due to its higher realism, positive influence on self-efficacy, and reduced level of distraction. Each of the five immersive properties explored in this study ('inclusive', 'extensive', 'vivid', 'empathy', 'atmosphere') generated positive psychological responses from users in regards to their learning experience, and achieved a more realistic simulation which may enhance students' conceptual learning. However, some negative consequences of these properties were identified and methods that may be used to suppress these consequences through simulation design choices are discussed below.

Specifically, more subtle effects such as realistic visuals and ambient audio (achieved by utilising the 'extensive', 'vivid', and 'atmosphere' properties) received unanimously positive responses as they did not trigger cognitive overload, unlike some participants' responses to the in-simulation dialogue (achieved by utilising the 'empathy' property).

Participants reported that the visuals, ambient audio, and the use of the engineering manager character within the high immersion simulation added to the realism of the simulation (question 1). A common psychological response from the low immersion simulation was boredom (e.g. "[The low immersion simulation]" is boring]). This mirrors the findings by Makransky & Peterson (2019) whereby realism had a positive relationship with presence and ultimately, motivation. The increase in students' perceived motivation when using the high immersion simulation may lead to an increase in conceptual learning.

All participants who responded to question 2 of the questionnaire (N = 8) reported that the high immersion simulation was most successful in generating self-efficacy. Reflecting on the positive relationship between self-efficacy and learning reported by Makransky & Peterson (2019), it is likely that the higher levels of perceived self-efficacy experienced while using the high immersion simulation had a positive influence on participants' conceptual learning.

Focusing on the auditory and visual components on each environment (question 3), twice as many students reported that the low immersion simulation was more distracting than the high immersion simulation. This was unexpected, as it was hypothesized by the authors that a lack of immersive properties would not have the potential to increase distraction. The auditory component of the high immersion simulation aided some students in reducing distraction by isolating them from the surrounding environment (achieved by utilising the 'inclusive' property), blocking out the surrounding environment. This finding echoes the characteristics of the 'inclusive' property, whereby the audio shuts the user out from the physical world. Hence, the utilisation of the 'inclusive' property is supported by an overwhelmingly positive psychological response from participants.

Several participants found the low immersion simulation to be more beneficial to their learning, because of the ease of communicating with the facilitator. It is possible that the simulations were not seamless in allowing users to be self-sufficient in completing the task, and participants required further instruction from the facilitator. In this case, some audio cues in the virtual environment acted as a distraction as the participant was unable to focus on communicating with the facilitator. Providing more instructional scaffolding within the simulation may have helped to prevent participants from removing their headphones and from communicating from the workshop facilitator. Furthermore, removing the ability for the player-character to begin the task before the initial dialogue had concluded may have reduced sensory overload when completing the task. The dialogue was beneficial to many participants and as such, removal of this property might have a negative effect on the virtual environment.

The teleportation mechanism that the user used to navigate the world provided no benefits and only worked to distract participants from the simulated task. This mechanism could be easily removed without altering the task and doing so would be beneficial to this specific simulation.

Reflecting on the research question (What is the relationship between conceptual learning and the use of immersive properties in head-mounted-display virtual reality simulations?) supports the finding that integrating immersive properties into simulations may be beneficial for enhancing students' conceptual learning. The explored immersive properties were successful in generating psychological responses of motivation and self-efficacy from participants. As a result, it is possible that the immersive properties increased the potential for conceptual learning outcomes.

The findings of this study have implications for developers of educational games and simulations, particularly in the engineering domain, who may be seeking to utilise head-mounted-display virtual reality simulations to promote conceptual learning. The limited surrounding literature prevents these parties from having access to experimental analysis on the interaction between immersion and learning. For this reason, these findings are intended as a resource for developers to inform the way they employ immersive properties in educational simulations.

Limitations and Future Work

A limitation of this study was that we did not attempt to test participants' actual learning. Instead, we explored reactions that could be reported by students (their perceptions), which have the potential to promote enhanced learning. This means that within the scope of this study, the 5 dimensions ('inclusive', 'extensive', 'vivid', 'empathy', 'atmosphere') were not able to be correlated with actual student learning in this context. However, as previously discussed, each of the five immersive properties explored in this study generated positive psychological responses from users in regards to their learning experience. The participants were also from a diverse cohort, and it is possible that undergraduate and postgraduate students may have different levels of experience with the concept addressed in the activity, which may have influenced the findings. Conducting the study on a larger scale and collecting quantitative data may offer more conclusive results to address these limitations.

The analysis in this study of the potential disadvantages of utilising or enhancing technological immersive properties in a simulation is limited. Specifically, the potential increase in cost and time in development, as well as the cost of elevated system requirements by the end user (predominantly GPU and CPU processing capabilities) are important to developers and educators. Evaluating these considerations would help to produce a quantifiable cost-benefit analysis which may be considered alongside the potential benefits that immersive properties can bring. It is recommended that future studies investigate this area.

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