Changing Physics Instruction by Synergizing Vygotskian Educational Theory and Virtual Reality

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Mixing Virtual Reality (VR) with Physics instruction is becoming more prevalent; however, many applications take a Piagetian learning approach, instructing first in a traditional way and then immersing students in VR without the instructor present. This paper proposes a design for a VR physics simulation that takes a Vygotskian approach using Zone of Proximal Development (ZPD) and scaffolding to teaching physics, allowing the students and instructor to collaborate in VR. It uses electromagnetism as a case study, along with a design-based research (DBR) research design paired with a Pedagogy Before Technology (PBT) approach to evaluate both usability and learning for the intervention. The result is a concrete experimental and research design proposing that a more effective VR environment would use the Vygotskian ideals of socialization and constructivism to encourage interaction between students during the scaffolded instruction period.

Keywords: physics education, Vygotsky, social constructionism, virtual reality, technology enhanced learning

INTRODUCTION

Virtual Reality in education had become a burgeoning field of research, with research having investigated the applications and effectiveness of VR in education and training since the 1980s (McLellan, 1996, 2003). Hu-Au and Lee (2007) demonstrated how educators can use virtual reality as a hands-on tool to teach more complex principles. Norriafshar et. al., (2014) studied how virtual reality can enhance instruction in nursing and business. However, research has only recently delved into how virtual reality can be more effective than traditional teaching in satisfying student motivation and engagement (Parong & Mayer, 2018).

Given this finding that motivation and engagement is higher using VR, the authors questioned whether an application of educational theories mixed with VR could be used not only to increase engagement, but also to bring improved learning outcomes for students in the base mathematics and physics concepts.

Traditionally, VR has been used in a sandbox component looking to increase engagement (Radianti et. al., 2020). We are looking to instead use Vygotskian teaching theories to create a VR Physics environment where a teacher can interact and manipulate physical constructs. In this paper, we are proposing that VR visualization can assist the learner in understanding concepts related to physics education, particularly with first year undergraduate students learning electromagnetic principles as a precursor to entering an engineering program. Specifically, the aim is to enhance student understanding of the relationships between the usually 'invisible' mathematics and the 'wow factor' of the physical outputs. The research question driving this project is "*How can a VR environment for physics education utilising Vygotskian concepts be used to enhance students' learning?*".

LITERATURE REVIEW

As technology becomes more prevalent in the education system, teaching and learning are undergoing drastic changes due to technological advances in the education field (Bereiter and Scardamalia, 2014). Disengagement is a key factor influencing student motivation, learning, and dropout rates (Appleton et al., 2006). The increase in student disengagement has created increased interest in using 3D immersion and VR applications, especially 360 VR videos, in educational practices, so students can engage in an immersive playback experience (Hosseini & Swaminathan, 2016). Innovative technologies such as virtual reality (VR) are not just altering the field of education for students, they are shaking up the role of educators and creating philosophical shifts in approaches to teaching and learning (Markowitz et. al., 2018).

Technology has become a powerful tool that creates a highly interactive 3D environment and provides users with an immersive, multisensory, real-time experience in a world which can manipulate or eliminate some of the physical constraints of the real world to enhance the ability to conceive complex Physics content (Mikropoulos & Natsis, 2011). Perkins et al (2006) developed PhET, a physics simulation program, so 2d animations can be used to represent physics concepts. PhET developed over 50 physics centred simulations for high school and college physics classes. However, the simulations themselves are not a virtual environment; they are a simpler 2d world constructed for each simulation with no indication if these simulations produced improved learning outcomes for students. In contrast, Wu, Chan, Jong & Lin (2003) and Kim, Park, Lee, Yuk & Lee (2001) propose a solution for using VR for physics that simulates wave forms, actions and reactions, harmonics, and electric currents through a 2-dimensional web view.

Looking at VR solutions which are more immersive, Loftin, Engleberg & Benedetti (1993) present a tethered immersive simulator with custom graphics hardware, allowing the manipulation of time as a variable and containing virtual switches, sliders and gravity controls. More recently, Pirker, Holly, Lesjak, Kopf & Gutl (2019) describe a system designed to provide an immersive virtual reality physics laboratory, MaroonVR, available in both seated and room scale versions. A basic multi-user version of MaroonVR is also available. Savage, McGrath, McIntyre, Wegener & Williamson (2010) describe a system called Real Time Relativity that uses virtual reality to explain physics concepts. However, the system used (immersive or not) is unclear, and the link to the website does not work, suggesting that the tool is no longer available. Kaufmann & Meyer (2009) describe a simulation that where students can manipulate forces on objects in virtual reality and uses a custom air pen and immersive headset in sandbox environment. Bogusevschi, Muntean & Muntean (2020) present results from a study in which virtual reality simulation of the water cycles are used to instruct secondary school students. In that VR environment, students can be placed in a realistic virtual world (the nature VR environment) or in an experimental VR environment to conduct experiments.

Looking at the integration of Virtual Reality (VR) in science fields, more specifically the physics field, the theoretical frameworks used is usually a Piagetian approach to learning and instruction (Dinham, 2017; Piaget, 1970; Piaget, 1950). In other words, Physics instruction chooses to implement VR as technology in which student utilizes the technology by themselves in an environment where they grapple with concepts alone and grapple using a constructivist framework. Piagetian theory (1970, 1950) believes students need to interact with physical properties in a self-directed environment which allows them to experience the struggle of complex information at their own pace. This framework also allows students to develop their own procedures for understanding the new material. This is a powerful form of learning because it provides student with agency in the learning process.

The predominant way of mixing Piagetian theories and VR is a sandbox format (Radianti et. al., 2020). In a sandbox format, students are instructed on the physics concepts in a traditional lecture format lacking the VR technology and later, post-instruction, can interact with predesigned VR sandbox representations of the concepts. This instructional pedagogy represents a Piagetian theory because students are left alone in a VR environment, so they can struggle through the disequilibrium component of physics concepts, without mathematical calculations, to derive at their own understanding of the curriculum.

We feel that using VR to teach physics could be enhanced by incorporating a Vygotskian component to the instructional process (Cowling & Vanderburg, 2020; Vanderburg, 2006; Vygotsky, 1989, 1986). Vygotskian theories would allow teachers to interact and instruct student in co-inhabited sandbox environment. Vygotsky argued instruction is conducted when a more experienced learner or instructor guides students with scaffolding through their Zone of Proximal Development (ZPD). The Zone of Proximal Development is a zone which spans from the point a student is unable to learn material or a task without some form of guidance (i.e., scaffolding) to the point in which they can learn the new material or task without guidance. Mixing Vygotskian theories with VR technology during the instructional component of the lesson would improve the students learning experience while integrating VR throughout the entire instructional process. The entire lesson would be conducted in a VR simulated environment. The instruction process would happen so the teacher can guide and interact with students working through virtual representations of the physics curriculum in a VR environment. This would enable the student to receive scaffolded virtual instruction from the teacher while learning the concepts in a virtual world. Once the VR instructional process is over the students would then be able to experience the Piagetian instructional experiences (Piaget, 1970, 1950) by being directed to the sandboxes.

A pedagogy which integrates Vygotskian (Vanderburg, 2006; Vygotsky, 1989, 1986) theories and VR guided physics instruction would improve the instructional process because the teacher is now able to teach the mathematical calculations of the physics curriculum in the virtual environment. Once the mathematics calculations are taught in the VR environment and, the mathematics calculations can be added to the sandbox environment in which the students work by themselves.

Using the virtual environment to teach the mathematics behind the physics principles would improve traditional instruction by allowing the teacher to manipulate the electrical field, the electric particles, the velocities of the particles, and the forces applied to the particles in the created VR world. Allowing students to have a visual representation of the possible changes to the variables in the experiment would help the students see, in a virtual environment, the math calculations which support the physics principles taught, and understand how the math relates to the physics principals. Adding the math calculation to the Vygotskian instructional component would improve instruction. It would also allow the sandbox component of the instructional process to be enhanced because teachers could add the mathematical values to the sandbox activities, which previously only encapsulated theoretical principles. Previously, the sandbox VR design could not provide mathematical explanations for the theoretical theories because students were unable to figure out the mathematical calculations without the teacher's assistance; the sandbox needs add a Vygotskian paradigm so students can be instructed on the mathematical procedures to practice them on their own. Because the math instruction is now added to the Vygotskian interactive VR instruction, math can be added to the sandbox component of the VR instruction. Mixing these two pedagogies with VR will enable students to better understand physics curriculum while improving their mathematical understanding of physics.

CURRICULUM DESIGN

The physics curriculum for this VR experiment will be 'electromagnetism' as related to the Australian Curriculum for senior Physics and the material in the Introductory Physics unit in the Skills for Tertiary Education Preparatory Studies (STEPS) enabling (or bridging) course at CQUniversity Australia (Cohalan, 2020). Specifically, we will be teaching about electric charges, fields and electric potential energy, magnetic fields and forces, and electromagnetic induction as part of three scenarios in VR.

The teaching for the first scenario will focus on the concept of electric charges; specifically, this section will focus on the visualisation of the electric fields around positively and negatively charged particles and the interactions of these fields when charges are brought near each other. The calculations will use the electric force formula for two charges, q_1 and q_2 separated by a distance r: $F_E = \frac{kq_1q_2}{r^2}$.

The second scenario will then introduce the concept of magnetic fields by introducing these charged particles into a representation of a magnetic field, B, and consider the motion and forces involved. For a charged particle, q, moving at a velocity, v, the force will be determined by: $F = qvB \sin\theta$ and the motion, in particular the radius, r, of the particle of mass, $mr = \frac{mv}{qB}$.

Finally, for the third scenario, the concept of electromagnetic induction will be presented by showing the same type of charged particles inside a cylindrical wire of length, l, and the wire being moved in a magnetic field as such generating a force by: $\varepsilon = Blv \sin\theta$. The force will result in the movement of the particles along the wire, representing the generated current. Further investigation of electromagnetic induction will show the reverse of the previous concept and will show visualisation of a magnetic field generated around a current carrying wire. The strength of the field, B, for current, I, at a point a distance, r, from the wire will be calculated by: $B = \frac{\mu_0 I}{2\pi r}$. In addition, this can demonstrate the cumulative effect of two wires that are brought into close proximity to each other. The same formula will be used for each wire to show how magnetic fields in current carrying wires create positive or negative interference.

EXPERIMENTAL DESIGN

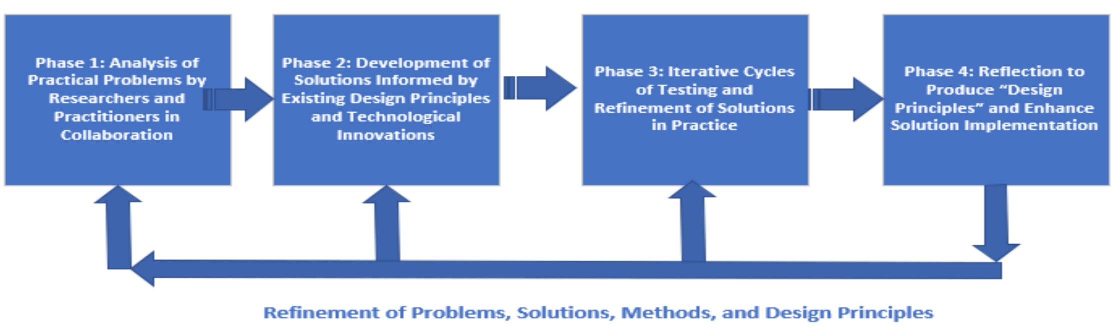
FIGURE 1
EXAMPLE OF THE ELECTRO ROOM VR ENVIRONMENT

The intervention design will build on the work of Cowling & Birt (2018), using a customised virtual reality intervention to teach electromagnetism. Specifically, the intervention will present a virtual classroom environment where the teacher will be able to model the three different electromagnetic principles in three different scenarios. The first scenario will visualise charged particles as balls of assorted colors and sizes to represent charges and masses with radiating lines of electric field around them. These fields will interact with each other, demonstrating electrostatic forces. These particles can also be moved through magnetic fields to demonstrate the electromagnetic force on these particles. In the second scenario, the teacher will be able to model an electrical wire shown as a cylinder containing charged particles. The teacher can then move the wire inside a magnetic field, and this will cause the movement of the particles along the cylinder as a depiction of the generated electric current. The third scenario will again have these cylinders of charged particles; however, the teacher will now create a current that generates concentric circles around the wire, depicting the generated magnetic field. Importantly for the implementation of the Vygotskian framework, students will be able to interact with other students and the instructor in the virtual environment (via each participant wearing their own headset), allowing for instruction to occur within the environment. The instructor will guide this interaction by taking control of the room and objects within it, whilst students can ask questions and see interactions through their headset. Students will also be able to copy numerical values from the simulation into their notebook to allow them to complete mathematical calculations using the formulas outlined above. An example of the environment is given in Figure 1.

RESEARCH DESIGN

This project will use a design-based research (DBR) methodology. This methodology supports exploration and adaptation through multiple cycles of data collection and refinement of the intervention. For example, the intervention will be improved based on feedback gained from the participant responses and investigator analyses retrieved from the multiple terms. This research approach is being used in education to investigate innovation using technology-based initiatives, because it "embraces the complexity of learning and teaching and adopts interventionist and iterative posture towards it" (Kelly, 2004, p. 105), allowing the design and development of authentic e-learning (Parker 2011). This study will be iterative in its methodology using the DBR process of Reeves (2006) as shown in Figure 2 (adapted from Munoz-Carpio, Cowling & Birt, 2018).

FIGURE 2
FOUR PHASES OF DESIGN BASED RESEARCH (REEVES, 2006)



The research will be conducted in two loops. The 1st loop will focus on talking to teachers of the unit, designing a solution, then testing it with the experts to make sure it is suitable. The 2nd loop will then refine the analysis and design based on the pilot with the experts, and then testing with students. the pedagogy of how physics concepts are taught will be engaged within the initial stages to ensure VR is an appropriate intervention will be explored, reflecting a Pedagogy Before Technology (PBT) approach to the development of the intervention (Cowling & Birt, 2018). The technology will then be implemented and

DBR techniques applied to iterate on design by engaging with the problem and solution.

Finally, this project will use a combination of qualitative and quantitative methodologies to answer our research questions. Usability testing will be conducted in-line with Birt & Cowling (2019), and a pre and post-test crossover design will be used to test learning outcomes. This approach aligns with the data sources available and allows for identification of the strengths and weaknesses of the VR Learning Model for Physics Education to improve physics teaching techniques while addressing our research questions.

CONCLUSION

Virtual reality is often presented in a sandbox style that echoes the work of Piaget in providing an isolated environment where students construct their own learning. Using physics education as a case study, this paper proposes a Vygotskian design for a Virtual Reality (VR) environment that teaches concepts of electromagnetism. Students would be able to use this VR intervention to manipulate physical objects, charges, visualize magnetic fields, and complete mathematical calculation using the resultant numerals. A Design Based Research methodology is then proposed to evaluate effectiveness of the intervention, implementing an underlying Pedagogy Before Technology approach evaluated through a combination of quantitative usability studies combined with qualitative and quantitative pre and post testing of learning outcomes. Through this intervention and evaluation, this paper proposes that a more effective VR environment would use the Vygotskian ideals of socialization and constructivism to encourage interaction between students during the scaffolded instruction period.

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