Investigating the Impact of Augmented and Virtual Reality on Learning in a Multivariable Calculus Classroom

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Abstract**—**Augmented reality (AR) and virtual reality (VR) applications were offered as supplemental learning experiences to a second-year multivariable calculus class. A framework of research-informed best practices was used to guide selection and application of AR and VR learning technologies. Student feedback indicated that both AR and VR enhanced learning, both would be of value to future students, and learning may be most enhanced when AR and VR are used as complementary learning tools. The simpler technology, AR, was generally preferred, but for specific topics, students felt that the more immersive VR learning experience was especially beneficial. Immersion in the virtual learning environment minimized distractions, allowed students to feel more connected to their learning, and enhanced their ability to visualize and interact with 3D objects. Resolution of identified accessibility concerns could improve students' overall experience with VR. Future research will explore ways to optimize the complementary effects of the two technologies. Application of research-informed framework of best practices was modelled throughout the study. Results and key resources informed revision and refinement of the framework.

Keywords**—**Accessibility, augmented reality, best practices, pedagogy, virtual reality.

I. Introduction

MATH 237, an introductory level multivariable calculus course, is designed to build student confidence in working with multivariable functions and prepare students for the study of advanced calculus. The interactive course textbook utilizes GeoGebra applets, providing 3D graphic models to complement algebraic representations of functions being studied. This technology has been shown to improve students' understanding of abstract concepts and enhance motivation, mathematical reasoning, and problem-solving skills [1]. Recent research suggests that learning might be further enhanced by offering 3D representations using augmented reality (AR) and/or virtual reality (VR) technologies [2]. The primary goal of this project is to use student feedback to assess how the use of supplementary AR and VR activities impact learning in a multivariable calculus classroom.

A. Extended Reality as a Learning Technology

Extended reality (XR) refers to a rapidly expanding group of 3D technologies that are generally categorized into three groups: AR, VR, and mixed reality (MR). Using a variety of computer-human interfaces, XR technologies enhance or replace the user's current physical environment [3]. AR applications add-on to (or augment) the learner's physical world, enhancing it digitally. AR allows instructors to layer virtual learning activities on top of real surfaces in books, on maps, or in actual physical locations and, depending on the application, may also allow students to interact with the augmentation [4]. VR applications are designed to immerse the learner in an artificial world, allowing them to feel physically present in a new environment where they are able to manipulate and interact with virtual objects while closed off from the actual physical world. Depending on the complexity, VR interactions can incorporate visual, auditory, tactile, and olfactory elements to increase the user's sense of actually being present in the virtual world [5]. MR combines AR and VR technologies in various ways. In recent years, use of XR in education has increased as it has become more affordable and more available.

In 2020, a systematic review of 38 conference and journal papers related to the use of immersive VR applications in higher education led researchers to conclude that, although interest in immersive technologies has increased, their impact on education remains suboptimal, due to poor implementation strategies and a poor understanding of pedagogy [6]. They emphasized that in order to ensure that XR learning activities are meaningful, enhance learning outcomes, and motivate students, they must be selected and utilized in ways that are based on sound pedagogical principles [6]. That same year, Long and Tsinakos developed a research-based framework of best practices for choosing, using, and designing XR learning applications [7]. This framework was later revised for use in post-pandemic learning environments [Appendix A] and this revised version informed the selection and use of AR and VR throughout this project. Secondary goals of this project include modelling the application of best practices for those considering using XR in their classroom and supporting the ongoing refinement of Long and Tsinakos' framework [Appendix A].

B. The Use of XR to Enhance Learning in Multivariable Calculus

Research has demonstrated that XR can enhance learning by allowing users to acquire knowledge and practice skills in settings that cannot otherwise be easily simulated for learning

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purposes due to constraints related to time, safety, finances, location, or mobility [8]. In the case of multivariable calculus, using XR as a learning tool allows students to not only visualize a mathematical representation in 3D, but also interact with that 3D representation: rotating it, viewing it from various angles and perspectives, making changes to it, and then viewing those changes from diverse perspectives. Such interactions are not currently available in other modes of learning.

Supplementing learning with XR activities that allow learners to receive feedback and repeat a learning experience in an environment where it is safe to make mistakes can lead to increased levels of skill mastery [9], increased confidence, and improved attitude toward learning [10]-[12]. Immersion in a virtual learning environment where activity repetition is allowed, and learners are able to manipulate and receive feedback on their interactions with multivariable functions can provide such an environment for calculus students.

Increased cognitive load in immersive learning environments has the potential to inhibit learning [13], [14], but researchers have identified several key strategies that can minimize this concern. These include providing learners with time to become familiar with the technology and allowing them to review key concepts before engaging with the learning experience [15], incorporating signaling techniques to direct learner attention to key concepts [16], designing experiences that are segmented and/or self-directed and which allow repetition of learning activities [14], and avoiding extraneous text or audio [13]. Each of these strategies have been incorporated into Long and Tsinakos' framework of best practices [Appendix A] (adapted from [7]) which has informed the design and implementation of this study.

Of great interest to those teaching multivariable calculus is Lai and Cheong's description of how the use of XR in teaching this subject can actually reduce cognitive load [2]. In comparing the use of XR with non-immersive multimedia, they indicate that "a key difference and advantage of XR is the representation of three-dimensional (3D) objects embedded in a 3D world. 3D thinking can be enhanced, and the mental transformation of information, not available on 2D interactive multimedia, can be facilitated [17]… reducing the cognitive load on the user" [2, p. 13693]. Lai and Cheong carried out a review similar to that done by Radianti's team [6] that focused specifically on research examining the use of XR in mathematics education. In doing so, they identified several potential benefits of using XR to enhance learning in the mathematics classroom: increased motivation [18]; development of spatial visualization skills [19], [20]; improved conceptualization of abstract ideas [21]; grade improvement and decreased attrition [22], [19]; increased engagement and motivation [23]. Lai and Cheong concluded that failure to align XR use with intended learning outcomes along with poor or sensationalized implementation of the technology can "severely hamper" [2, p. 13695] its effective use. Consequently, in 2022, they developed a four-point framework to guide the effective development and use of XR learning activities [2]. This framework focuses on designing XR learning activities to align with specific learning outcomes, identification and incorporation of learning requirements associated with the specific learning stage and pedagogical needs of the users, soliciting feedback from learners to ensure that the learning activity actually meets the needs of learners and achieves the identified learning outcomes, and engaging in ongoing revision and refinement of the XR learning activities in response to feedback received [2]. In alignment with Lai and Cheong's [2] recommendations, this project aims to use learner feedback to assess whether learning activities meet the needs of learners in order to inform future revision and refinement.

II. Methodology

A. Technology Selection

GeoGebra and CalcVR were identified as AR and VR applications respectively that have been used by others to enhance learning in multivariable calculus [24]-[26].

- The GeoGebra AR application allows learners to walk around, observe from various perspectives, and take screenshots of 3D mathematical objects in their own environments [24], [26]. The open-source nature of the application allows instructors to tailor interactions to the needs of learners.
- The CalcVR application uses a smartphone and the Google Cardboard framework to provide VR lessons and demonstrations to enhance multivariable calculus learning [27]. Interactive elements interspersed throughout the lessons are used to assess learning and provide feedback to the learner.

In considering whether these two applications would be suitable learning tools for this study, Long and Tsinakos' "Best Practices for Choosing XR Learning Applications" was consulted [Appendix A] (adapted from [7]). Criteria considered are outlined in Table I.

TABLE I
BEST PRACTICE CRITERIA CONSIDERED DURING APP SELECTION

Criteria	Description	GeoGebra	CalcVR
Cost	Application is available at no cost	✓	✓
Pedagogy	Able to support course learning outcomes	✓	✓
	Content designed specifically for XR	✓	✓
Accessible technology	Accessed using a smartphone or tablet	✓	✓
Ease of use	Minimal user frustration	✓	✓
	Clear navigational cues	✓	✓
Segmentation/ Self-direction	Learning is interspersed with knowledge checking activities and/or is self-directed and self-paced	✓	✓
Support	Multiple user supports available	✓	✓
Privacy	No user information collected/shared	✓	✓
Level of Immersion	Minimized to lower equipment costs and cognitive load	✓	✓

All listed criteria come from Long and Tsinakos' "Best Practices for Choosing XR Learning Applications" [Appendix A].

Lai and Cheong [2] emphasize the importance of ensuring that the development of XR learning activities for the mathematics classroom has involved both educators who are knowledgeable in pedagogy and technical experts who can optimize the potential of the technology. They explain that collaborative efforts that draw upon both areas of expertise are better able to ensure that learning activities achieve specific learning outcomes, are designed to suit the learning stage of the learners and make effective use of the technology to engage and motivate learners [2]. Both GeoGebra and CalcVR align with these recommendations:

- Development of the CalcVR lessons was a collaborative effort between Dr. Jeremy Becnel and Dr. Nicholas Long [27] who together brought expertise in both mathematical pedagogy and VR technology to the project. Lessons were designed specifically for post-secondary mathematics students to achieve specific learning outcomes outlined in the website's supplementary materials area [27]. Instructions and feedback within each activity were also tailored to the learning needs of this student group. Throughout the development process, Long and Becnel sought learner feedback, using it to revise and refine the learning activities and optimize learning [27].
- Development of GeoGebra AR, an open source, dynamic software designed for use in the mathematics classroom, involved collaboration between those with both pedagogical and technological expertise. The open-source nature of the tool allows educators to easily create activities that both achieve specific learning outcomes and suit the specific learning stage of the users [28].

B. Activity Selection

The selection of CalcVR activities and the development of GeoGebra AR activities to be used as part of each tutorial aligned with both Long and Tsinakos' "Best Practices for Using XR Learning Applications" [Appendix A] and Lai and Cheong's recommendations [2]:

- Using the learning outcomes identified on the CalcVR website [27], the primary investigator, a former Math 237 instructor, selected lessons that would meet the intended learning outcomes of the course and the needs of the learners. Tutorial dates selected ensured that students would have been introduced to key concepts in class prior to engaging with the relevant VR activity.
- Each GeoGebra AR activity was designed by the primary investigator to align with a selected CalcVR activity and with course learning outcomes. During the tutorial, the primary investigator introduced each activity and provided feedback as needed.

C. Tutorial Design

Participants were students enrolled in Math 237 who voluntarily chose to participate by responding to an email invitation and subsequently committed to participating in three tutorials over the course of the term. Each of the three tutorial sessions had a similar format:

1. Upon arrival, the student was welcomed and given a consent form to review and sign (first tutorial only).
2. The student was seated in a chair that allowed them to rotate while remaining seated in order to prevent injury and minimize cybersickness.
3. The research team reviewed the tutorial agenda and the purpose of the research project with the student, reviewed key concepts and made connections with course materials, demonstrated safe and proper use of the VR equipment, and offered assistance adjusting the headset, while inviting and answering questions.
4. The student completed the CalcVR introductory lesson (first tutorial only) followed by the VR activity associated with the tutorial.
5. The student was encouraged to pause and reorient themselves prior to beginning the AR activity.
6. The research team introduced the AR equipment, demonstrated safe and proper use, and provided an overview of the AR activity, while inviting and answering questions.
7. The student completed an AR activity designed by the primary investigator to complement the VR lesson.
8. The student completed an anonymous online Qualtrics feedback survey.
9. All equipment was sanitized between users.

Long and Tsinakos' second framework component, "Best Practices for Using XR Learning Applications" [Appendix A] (adapted from [7]) informed the design and delivery of the tutorial sessions. Criteria considered are outlined in Table II.

TABLE II
BEST PRACTICE CRITERIA CONSIDERED IN TUTORIAL DESIGN

Criteria	Description
Activity Selection	Designed (GeoGebra) or selected (CalcVR) to achieve course learning outcomes.
Equipment	No cost to students (funded by the faculty); selected to ensure low cost overall
Number and Frequency	3 tutorials spaced 1-2 weeks apart to allow students to become comfortable with the technology
Duration	30 minutes per student
Pace	Self-paced with breaks and repetition as needed
Group size	Individual to minimize distractions and ensure personalized support
Timing	After key concepts had been introduced in class
Support	Two members of the research team were present throughout each tutorial. Support varied with student needs and included an introduction to each technology and its safe use, a review of the theory behind each lesson/activity, answering questions, ensuring equipment fit properly, troubleshooting when needed, and watching and responding to signs of participant confusion or discomfort.
Feedback	Collected at the end of each tutorial and reviewed at the end of the study to inform future revision and refinement of activities

All listed criteria come from Long and Tsinakos' "Best Practices for Using XR Learning Applications" [Appendix A].

Both Long and Tsinakos [7] and Lai and Cheong [2] emphasize the importance of using XR learning activities to enhance rather than replace pre-existing learning experiences. This practice prevents the exclusion of learners who are unable to engage with the XR activity due to cybersickness or other accessibility limitations [2]. Offering XR learning activities in addition to other modes of learning also aligns with Universal Design for Learning (UDL) guidelines. These guidelines offer educators a set of concrete suggestions for providing learners with multiple means of engagement, representation, action, and expression, thus ensuring that meaningful learning opportunities are available for all learners [29]. In alignment with these recommendations, all three tutorials were optional, designed to enhance rather than replace pre-existing learning experiences.

III. Results

Feedback collected after each tutorial session is summarized in Tables III-X. Since the number of participants varied in each tutorial (9, 6, and 3 in Tutorials 1, 2, and 3 respectively) student ratings are expressed as percentages throughout. In each tutorial, 100% of participants provided feedback.

Within the anonymous feedback survey, students were also invited to explain if and/or why they preferred one technology over another and to share additional thoughts.

TABLE III
STUDENT OVERALL EXPERIENCE WITH GEOGEBRA/CALCVR

Tool	Tutorial	Student Rating (%)				
		Very Poor	Poor	Neutral	Positive	Very Positive
GeoGebra	1	0	11	11	78	0
	2	0	20	0	80	0
	3	0	0	0	0	100
CalcVR	1	11	0	44	33	12
	2	20	20	0	60	0
	3	0	33	33	34	0

TABLE IV
DEGREE THAT GEOGEBRA/CALCVR WAS HELPFUL TO LEARNING

Tool	Tutorial	Student Rating (%)				
		Not at all	A bit	Moderately	Very	Extremely
GeoGebra	1	0	22	45	33	0
	2	0	20	40	20	20
	3	0	0	0	100	0
CalcVR	1	11	33	33	11	11
	2	40	0	20	20	20
	3	0	33	67	0	0

TABLE V
GEOGEBRA ELEMENTS THAT STUDENTS FELT ENHANCED LEARNING

Element	Student Rating (%)		
	Tutorial #1	Tutorial #2	Tutorial #3
Visualizing the function/object in 3D	100	100	100
Ability to interact with the 3D function	67	100	33
Controls/navigation	33	0	67

TABLE VI
GEOGEBRA ELEMENTS THAT STUDENTS FELT INHIBITED LEARNING

Element	Student Rating (%)		
	Tutorial #1	Tutorial #2	Tutorial #3
Visualizing the function/object in 3D	0	0	0
Ability to interact with the 3D function	17	0	33
Controls/navigation	100	80	33

TABLE VII
CALCVR ELEMENTS THAT STUDENTS FELT ENHANCED LEARNING

Element	Student Rating (%)		
	Tutorial #1	Tutorial #2	Tutorial #3
Visualizing the function/object in 3D	56	100	100
Ability to interact with the 3D function	67	40	33
Controls/navigation	22	40	0

TABLE VIII
CALCVR ELEMENTS THAT STUDENTS FELT INHIBITED LEARNING

Element	Student Rating (%)		
	Tutorial #1	Tutorial #2	Tutorial #3
Visualizing the function/object in 3D	22	0	0
Ability to interact with the 3D function	11	40	33
Controls/navigation	78	40	100

TABLE IX
PREFERRED LEARNING TOOL

Element	Student Rating (%)		
	Tutorial #1	Tutorial #2	Tutorial #3
GeoGebra	22	60	0
CalcVR	78	40	100

TABLE X
HELPFULNESS OF SUPPLEMENTARY XR ACTIVITIES FOR FUTURE STUDENTS

Tutorial	Student Rating (%)				
	Not at all	A bit	Moderately	Very	Extremely
1	0	33	22	33	11
2	0	20	20	40	20
3	0	0	0	0	100

IV. Discussion

A. Diminishing Number of Participants

Student participation decreased by about one third for the second tutorial and again for the third. Several factors may have contributed to this decrease:

1. As the exam period approached, students may have become increasingly overwhelmed with project deadlines and studying, leading them to opt out of participating in non-essential activities.
2. Students who identified accessibility concerns related to text size, color, and contrast may have been less likely to continue participating.
3. Cybersickness and/or dizziness experienced during the VR activities may have also led some students to withdraw from participation

B. Overall Experience

Students rated their overall experience with both XR technologies positively. Their ratings generally favored GeoGebra, a trend that increased over the course of the three tutorials (Fig. 1) but CalcVR was also rated well, especially in Tutorial 2. Research has demonstrated the value of allowing students to interact with a technology repeatedly, showing that student learning improves if they are given time to become comfortable with a technology [30]. In this study, students did seem to become more comfortable with GeoGebra overtime; at the end of Tutorial 3, one student described it as "easy and comfortable to use". The same is not true for CalcVR. Concerns related to accessibility and controls may account for the difference.

C. Accessibility Concerns

Student feedback on their experience with CalcVR indicated that text size, color, contrast, and general visibility varied between lessons. During Tutorial 1, one student indicated that their color-blindness made it difficult for them to distinguish between the colors used in the CalcVR activity. Another student described the text in CalcVR Tutorial 2 as "much better to see" than that in Tutorial 1. Despite the apparent improvement in text visibility in Tutorial 2, student feedback highlighted that headset fogging led to blurring of the already "tiny" text. Improvements in visibility and text size in Tutorial 2 may have been one factor that contributed to CalcVR being rated as the preferred technology during this tutorial whereas GeoGebra was preferred for Tutorials 1 and 3 (Fig. 2).

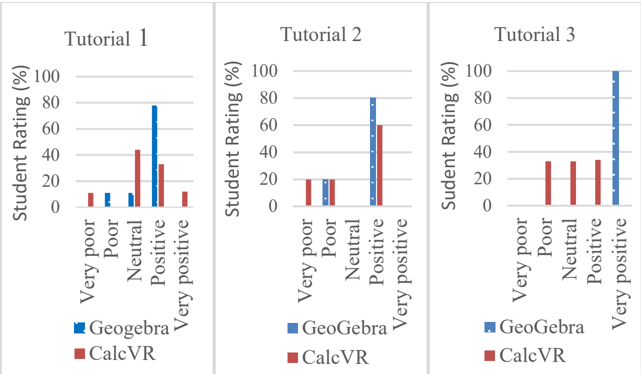

Fig. 1 Comparison of students' overall experience

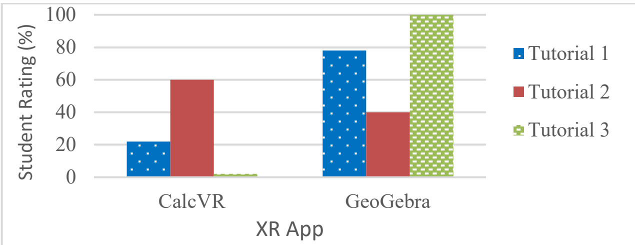

Fig. 2 Learning tool preference

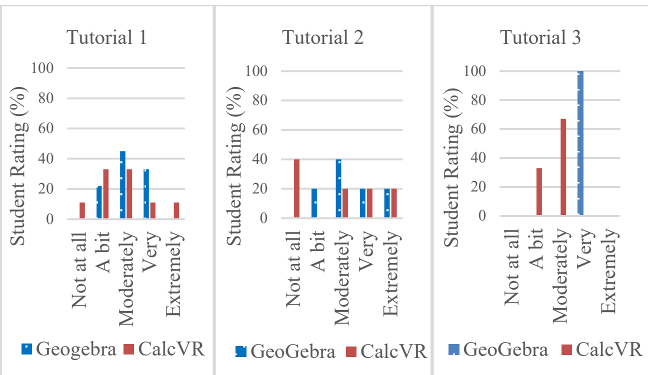

Fig. 3 Comparison of how helpful students found AR and VR to be in learning math

An important resource to consider when developing XR learning applications is the Web Content Accessibility Guidelines (WCAG) developed by the World Wide Web Consortium (W3C). These guidelines offer developers a standard to follow when designing websites, apps, electronic documents, and other digital assets in order to make them accessible to people with a broad range of disabilities, including sensory, intellectual, learning, and physical disabilities. The concerns raised in the student feedback survey (font size, contrast, and color choice) are addressed by these guidelines [31].

Although the W3C guidelines can be helpful, technological limitations may hinder efforts to make XR learning activities accessible. A CalcVR developer indicated that accessibility issues such as those raised in the feedback survey can be difficult to resolve when the host technology is a mobile phone, a device that was never originally intended to host VR. They pointed out that in May 2022, CalcVR was modified for use on the Meta Quest 2 headset, and it is now freely available on the Oculus App Labs. They indicated that accessibility concerns have been reduced in this new format since the host technology is a VR headset intended and designed for use with VR. Although this transition may eliminate certain accessibility concerns, it creates others. The Meta Quest 2 headset is less financially accessible to users due to its higher cost. It would not currently be a feasible option to purchase Meta Quest 2 headsets for use in Math 237.

D.Cybersickness

Another factor that varied between CalcVR lessons was incidence of cybersickness. The Qualcomm Developer Network (QDN) describes cybersickness as a phenomenon that occurs when "motion portrayed in the viewport is detected by our visual sense but does not match the motion detected by our vestibular sense" [32, p.3]. Not all VR users experience cybersickness and those who do may experience it inconsistently [33]. In this study, Tutorial 2 seemed to leave students more vulnerable to experiencing this discomfort. One student struggled with cybersickness to the extent that they were unable to complete Tutorial 2 and did not return for Tutorial 3. The QDN identifies system, application, and individual factors that can play a role in whether users experience cybersickness [32]. Since the hardware did not change between tutorials in this study, and users were asked to refrain from participating if they were unwell, these system and individual factors have been controlled. Consequently, it is worthwhile considering how application factors may have contributed to increased cybersickness during Tutorial 2. The QDN identifies duration, visual acceleration, frequency, intensity of head motion, and insufficient user control as application factors that may increase the incidence of cybersickness [32]. Considering that Tutorial 2 did not have the longest duration and students were seated in a rotating chair in order to minimize the need for head movement in all three tutorials, the difference may lie in how the student interacted with the function within the lesson. This will be brought to the attention of the CalcVR developer for future consideration. The QDN guidelines for reducing cybersickness [32] can be a valuable resource for those developing XR for learning.

E. Student Learning

Despite varying tool preferences (Fig. 2), when asked which tool was most helpful in learning math, students rated

GeoGebra higher than CalcVR every time (Fig. 3). In order to better understand these findings, it may be helpful to consider specific aspects of each tool that students felt enhanced or inhibited learning.

1. Controls

Fig. 5 demonstrates that controls were, at times, problematic for both technologies but the extent to which this was true varied between activities. After Tutorial 3, a student commented that "CalcVR… introduces difficulties in navigation which are not present with [GeoGebra]". Despite these frustrations related to controls, after Tutorial 3 a student expressed appreciation for CalcVR's ability to "get me involved in the learning environment and be more focused on the topic".

2. Visualizing the Function in 3D

Fig. 4 demonstrates that students found both technologies helped them visualize the function in 3D. In Tutorials 1 and 3, students indicated that GeoGebra did this in a way that was more beneficial to learning than CalcVR, but in Tutorial 2 both technologies were rated as very helpful (Fig. 6). A student commented after Tutorial 2 that both GeoGebra and CalcVR were "very helpful in visualizing 3D objects, and specifically tangent lines" suggesting that visualizing the object in 3D was especially beneficial for the specific topic being investigated in Tutorial 2.

3. Ability to Interact with the 3D Function

Fig. 4 indicates that, in Tutorials 1 and 3, both technologies facilitated interaction with the 3D object in a way that was beneficial to learning, but in Tutorial 2, CalcVR was less able to facilitate this kind of helpful interaction than GeoGebra. Still, student comments after Tutorial 2, indicated that CalcVR "helped eliminate distractions allowing for increased engagement in the lesson" and that students appreciated CalcVR's built in opportunities for checking learning.

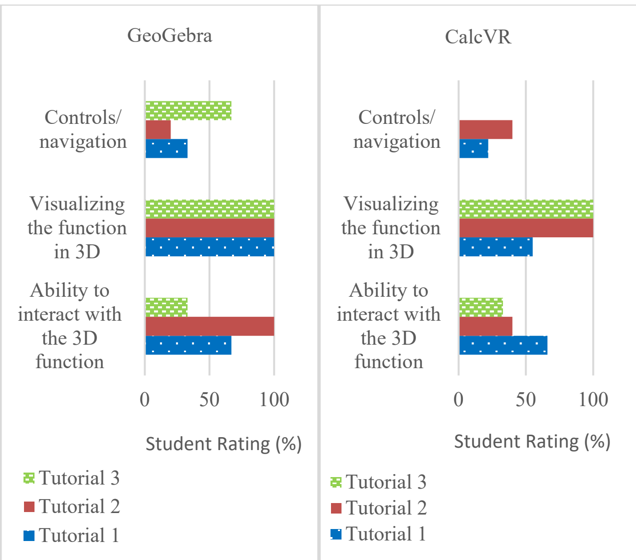

Fig. 4 Factors students felt enhanced learning

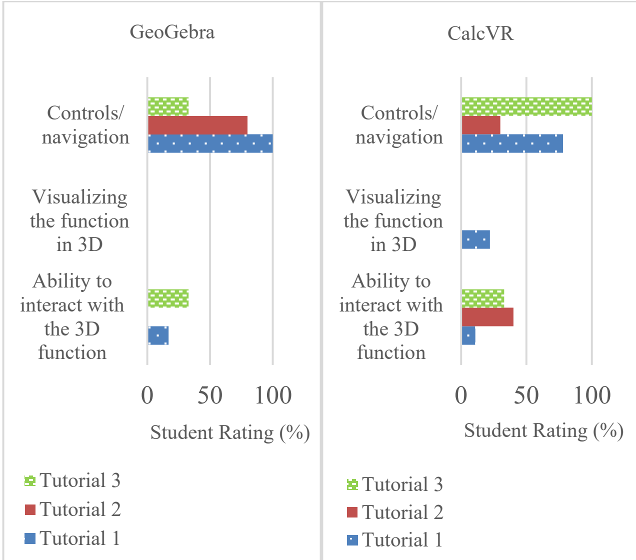

Fig. 5 Factors students felt inhibited learning

After Tutorial 1, a student described both technologies as helpful but described GeoGebra as "less of a hassle", presenting the function more clearly, allowing for more self-direction and providing an increased sense of connection with their environment. Overall, survey results and student comments demonstrate that students saw value in both technologies, that both technologies enhanced learning, and that preferences varied depending on the topic being studied.

F. Benefits for Future Students

Students ultimately felt that XR technologies could enhance the learning of future students (Fig. 6). The extent to which this was true increased over the course of the three tutorials.

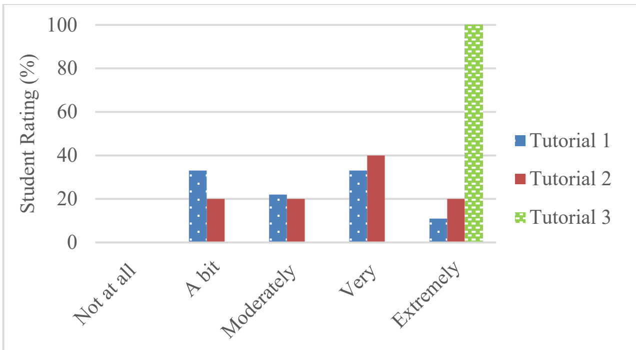

Fig. 6 Helpfulness of supplementary XR activities to future Math 237 students

V. Conclusions and Future Directions

The primary goal of this project was to gather student feedback to assess how the use of supplementary AR and VR activities impacts learning in a multivariable calculus classroom.

Feedback gathered indicated that students found both AR and VR technologies enhanced learning and that both would be of value to future students. Student feedback indicated that learning may be most enhanced when AR and VR are used as complementary learning tools rather than offering one or the other exclusively.

- Due to its simplicity, AR was generally preferred as it allowed students to visualize and interact with 3D concepts using less cumbersome technology.
- For specific topics, students felt the more immersive VR learning experience was especially beneficial. Immersion in the virtual learning environment minimized distractions, allowed students to feel more connected to their learning, and increased their ability to visualize and interact with 3D objects.
- Resolving accessibility concerns related to small text, poor color contrast, and cybersickness could improve students' overall experience with VR. Although these concerns may be resolved by moving to a platform designed for VR like the MetaQuest2 VR headset, such a move can introduce financial barriers.

Instructors can weigh the strengths and weaknesses of each technology when considering which would enhance a specific lesson, or they can make both available, allowing students to engage with the experiences that they find most helpful.

Future research will explore ways to optimize the complementary effects of the two technologies.

Secondary goals of this project included refining Long and Tsinakos' framework of best practices [Appendix A] and modelling its application in order to guide instructors in creating learning experiences that are informed by research-based best practices. Insights related to Lai and Cheong's recommendations [2], accessibility concerns raised by students, and QDN's strategies to minimize cybersickness [32] have informed these revisions and the "Revised Framework for Choosing, Using, and Designing XR Learning Applications" is included in Appendix B.

APPENDIX A

Framework for Choosing, Using, and Designing XR Learning Applications

The three sets of best practices outlined below make up a framework to guide instructors and developers in working collaboratively to effectively design and use XR as a tool for learning and knowledge sharing. Tables XI-XIII are adapted from [7] and used with permission.

TABLE XI
BEST PRACTICES FOR CHOOSING XR LEARNING APPLICATIONS

Topic	Best Practices
Pedagogical Design	Choose an XR application that facilitates achievement of preset learning outcomes, enhances but does not replace other modes of learning, and aligns with the most recent teaching and learning research related to the specific student group.
Accessibility	Choose a technology with accessibility features that provide multiple means of engagement in order to support the needs of learners with diverse abilities. Provide alternate modes of learning when this is not possible.
Accessible technology	Choose XR applications that can be accessed on smart phones, tablets, and personal computers.
Costs	Minimize costs for both instructors and students. Use free technology when possible.
Connectivity	Avoid XR technologies that require large downloads and if possible, select a tool that can be used offline.
Support	Choose XR applications with reliable, effective support for students and instructors
Segmentation/ Self-direction	Choose an XR application that facilitates segmentation allowing learning to be divided into short chunks or, when this is not possible, facilitates student-directed learning.
Level of Immersion	Choose a less immersive XR technology when it will provide an equally effective learning experience that fulfills learning outcomes.
Ease of Use	Minimize distractions and frustration by choosing an XR technology that is reliable and easy to use with clear navigational cues.
Repetition	Choose a technology that can facilitate repetition of the learning experience
Effectiveness	Choose an XR application that allows for monitoring and revision as needed to ensure ongoing achievement of learning outcomes.
Privacy	Determine what information will be collected by the technology, how it will be used, where it will be stored, how this may impact your learners, and whether it aligns with the policies of your institution.

TABLE XII
BEST PRACTICES FOR USING XR LEARNING APPLICATIONS

Topic	Best Practices
Pedagogical Design	Use the XR technology in a way that facilitates achievement of preset learning outcomes, enhances but does not replace other modes of learning, and aligns with the most recent teaching and learning research related to the specific student group.
Accessibility	Use available accessibility features fully to maximize opportunities to engage with the learning activity. Provide alternate modes of learning when a fully accessible experience is not possible.
Accessible Technology	Ensure students have the option of accessing the learning using smart phones, tablets, and personal computers.
Supplement	Offer the XR learning application as one of several representations of the learning material. Use it to enhance but not replace other modes of learning.
Preparation	Provide learners with plenty of time to become familiar with the technology prior to the learning experience.
Pretraining	Familiarize students with key concepts and navigational cues prior to the learning activity.
Support	Provide learners with reliable, effective support throughout the learning experience.
Segmentation/ Self-direction	If the application does not already do so, divide XR learning into short chunks, interspersing these with breaks, generative activities, formative assessment, and/or opportunities to repeat or review the learning. Where segmentation is not possible, provide learning experiences that are student-directed with plenty of time for student-initiated breaks, review, and/or repetition.
Distractions	Minimize distractions and interruptions from outside sources that can prevent learners from fully engaging in the learning activity.
Repetition	Encourage repetition of the XR learning experience, especially more immersive experiences that tend to have a higher cognitive load.
Effectiveness	Evaluate the XR experience regularly to ensure ongoing achievement of learning outcomes. Revise learning experiences as necessary.
Privacy	Use applications in ways that will minimize collection and sharing of personal information and align with the policies of your institution.

TABLE XIII
BEST PRACTICES FOR DESIGNING XR LEARNING APPLICATIONS

Topic	Best Practice
Pedagogical Design	Design an XR application that allows educators to adapt the material and revise as needed in order to ensure achievement of preset learning outcomes in their unique setting, that is intended to enhance but not replace other modes of learning, and which aligns with the most recent teaching and learning research related to the specific student group.
Accessibility	Incorporate accessibility features into the design to support the needs of learners with diverse abilities. Provide multiple means of engagement. When this is not possible, ensure that alternate forms of learning are also made available.
Accessible Technology	Design XR applications that can be accessed on smart phones, tablets, and personal computers.
Cost	Minimize costs for both instructors and learners. Create tools that can be offered for free, when possible.
Connectivity	Avoid designing XR applications that require large downloads. If possible, design a tool that can be used offline.
Level of Immersion	Design less immersive XR applications when they will provide an equally effective learning experience that fulfills learning outcomes.
Simplify the experience	Avoid extraneous use of images, text, and audio to minimize distractions and decrease cognitive load.
Ease of Use	Minimize frustration by designing XR applications that are easy to use. Ensure that technical support is reliable and easy to access. Build in effective navigational cues.
Segmentation/ Self-direction	Where possible, design XR learning that is presented in short chunks interspersed with breaks, generative activities, formative assessment, and/or opportunities to repeat or review the learning. Where segmentation is not possible, design learning experiences that are student-directed.
Signaling	Incorporate features that highlight key learning concepts to signal their importance to students.
Repetition	Design XR applications that encourage repetition, especially with more immersive experiences that tend to increase cognitive load.
Minimize distractions	Design the XR application to minimize distractions and interruptions allowing learners to fully engage in the learning activity.
Monitor Effectiveness	Evaluate the design of the XR application throughout the development process to ensure ongoing achievement of learning outcomes. Revise as needed.
Privacy	Design XR applications that do not collect, store, or share personal information.

APPENDIX B

Updated Framework for Choosing, Using, and Designing XR Learning Applications

The three sets of best practices outlined below make up a framework to guide instructors and developers in working collaboratively to effectively design and use XR as a tool for learning and knowledge sharing. Tables XIV-XVI are adapted from [7] and used with permission.

TABLE XIV
BEST PRACTICES FOR CHOOSING XR LEARNING APPLICATIONS

Topic	Best Practices	Literature References
Learning Outcomes	Identify desired learning outcomes and select a learning application that can achieve those outcomes, soliciting learner feedback to assess whether outcomes are being met.	[6] [2]
Learner needs	Assess the specific needs of the intended group of learners as they relate to a preferred pedagogical taxonomy. Choose a learning application that is able to meet those needs, soliciting learner feedback to assess whether needs are being met.	[2]
Accessibility	Choose a learning application that supports the needs of learners with diverse abilities. Involve persons with disabilities in the selection process.	[34]
	Choose a learning application that aligns with the following external accessibility guidelines: Web Content Accessibility Guidelines (WCAG) with respect to text size, colour, contrast, etc.	[31]
	UDL guidelines with respect to providing multiple means of engagement, representation, action, and expression.	[29]
	Consider what hardware is readily available to learners (desktop, mobile devices, HMDs) and choose applications that utilize these technologies. Consider connectivity limitations of learners and avoid choosing applications that require a greater level of connectivity than is reliably available.	[35]
Costs	Minimize costs for both instructors and students. Use free technology when possible.	[35]
Support	Choose XR applications for which effective and reliable support is available to both students and instructors	[35]
Segmentation/ Self-direction	Choose an XR application that facilitates segmentation allowing learning to be divided into short chunks and/or facilitates student-directed learning.	[14]
Signaling	Choose an XR application that facilitates the use of signaling to direct students' attention to key concepts to be learned.	[16]
Level of immersion	Choose a level of immersion appropriate to the subject matter ensuring that cognitive load is minimized and learning outcomes are met.	[2] [14]
Ease of Use	Minimize distractions and frustration by choosing XR technologies that are reliable, easy to use, and have clear navigational cues.	[36] [8]
Repetition	Choose a technology that can facilitate repetition of the learning experience	[14]
Privacy	Determine what information will be collected by the technology, how it will be used, where it will be stored, how this may impact your learners, and whether it aligns with the policies of your institution.	[35]

TABLE XV
BEST PRACTICES FOR USING XR LEARNING APPLICATIONS

Topic	Best Practices	Literature References
Learning Outcomes	Identify desired learning outcomes and utilize appropriate features of the learning application in ways that will ensure that those outcomes will be achieved, soliciting learner feedback to assess whether outcomes are being met.	[6] [2]
Learner needs	Assess the specific needs of the intended group of learners as they relate to a preferred pedagogical taxonomy. Utilize appropriate features of the learning application in ways that will ensure that those needs will be met, soliciting learner feedback to assess whether needs are being met.	[2]
Accessibility	Use the learning application in ways that support the needs of learners with diverse abilities.	[34]
	Involve persons with disabilities in the process of planning how the learning application will be used.	
	If the application can be used with various types of hardware (desktop, mobile devices, HMDs), plan to use it on the hardware that is most readily available to learners.	[35]
	Plan to use the application in ways that consider and accommodate connectivity limitations of learners.	[31]
	Consider the following external accessibility guidelines when planning how to best use XR learning applications:	
	Web Content Accessibility Guidelines (WCAG) with respect to text size, colour, contrast, etc.	[29]
	UDL guidelines with respect to providing multiple means of engagement, representation, action, and expression.	
	Consider strategies for reducing cybersickness when planning to use the XR application.	
Supplement	Offer the XR learning application as one of several representations of the learning material. Use it to enhance but not replace other modes of learning.	[2]
Preparation	Provide learners with plenty of time to become familiar with the technology prior to the learning experience.	[15], [30]
Pretraining	Familiarize students with key concepts and navigational cues prior to the learning experience.	[15]
Support	Provide learners with reliable, effective support throughout the learning experience.	[35]
Segmentation/ Self-direction	If the application does not already do so, divide XR learning into short chunks, interspersing these with breaks, generative activities, formative assessment, and/or opportunities to repeat or review the learning. Where segmentation is not possible, provide learning experiences that are student-directed with plenty of time for student-initiated breaks, review, and/or repetition.	[14]
Signaling	Use signaling within the XR learning activity to direct students' attention to key concepts to be learned	[16]
Minimize distractions	Minimize distractions and interruptions from outside sources that can prevent learners from fully engaging in the learning activity.	[36] [8]
Repetition	Encourage repetition of the XR learning experience, especially more immersive experiences that tend to have a higher cognitive load.	[14]
Monitor Effectiveness	Gather feedback from learners throughout the development process to ensure that learning outcomes are being achieved and learner needs are being met; revise as needed	[2]
Privacy	Use applications in ways that will minimize collection and sharing of personal information and align with the policies of your institution.	[35]

TABLE XVI
BEST PRACTICES FOR DESIGNING XR LEARNING APPLICATIONS

Topic	Best Practices	Literature References
Learning Outcomes	Identify desired learning outcomes and design the activity to achieve those outcomes, soliciting learner feedback to assess whether outcomes are being met and revising accordingly.	[6] [2]
Learner needs	Assess the specific needs of the intended group of learners as they relate to the preferred pedagogical taxonomy. Design the activity to meet those needs, soliciting learner feedback to assess whether needs are being met and revising accordingly.	[2]
Accessibility	Incorporate accessibility features into the design to support the needs of learners with diverse abilities. Utilize appropriate strategies (e.g., creation of learner personas, scripting, and storyboarding) to facilitate this process.	[34]
	Involve persons with disabilities in the design process.	
	Consider the following external accessibility guidelines and, where possible, design XR learning applications to align with them:	
	Web Content Accessibility Guidelines (WCAG) with respect to text size, colour, contrast, etc.	[31]
	UDL guidelines with respect to providing multiple means of engagement, representation, action, and expression.	
	Design applications that can be hosted on hardware that is readily accessible to instructors and learners.	[29]
	Consider connectivity limitations of learners. Avoid designing XR applications that require large downloads. If possible, design a tool that can be used offline.	[35]
	Incorporate strategies for reducing cybersickness into the application's design.	[32]
Cost	Minimize costs for both instructors and learners. Create tools that can be offered for free, when possible.	[35]
Support	Build in user supports where possible. Ensure that external supports are reliable, effective, and easily accessible.	[35]
Level of Immersion	When designing learning applications, consider what level of immersion is most appropriate to the subject matter ensuring that cognitive load is minimized and learning outcomes are met.	[2] [14]
Simplify the experience	Avoid extraneous use of images, text, and audio to minimize distractions and decrease cognitive load.	[15]
Ease of Use	Minimize frustration by designing XR applications that are easy to use, providing clear navigational cues and intuitive design features.	[36] [8]
Pretraining	Build in opportunities for students to become familiar with key concepts and navigational cues before they use the learning activity.	[15]
Segmentation/ Self-direction	Where possible, design XR learning that is presented in short chunks interspersed with breaks, generative activities, formative assessment, and/or opportunities to repeat or review the learning. Where segmentation is not possible, design learning experiences that are student-directed.	[14]
Signaling	Incorporate features that allow key learning concepts to be highlighted to signal their importance to students.	[16]
Repetition	Design XR applications that encourage repetition, especially with more immersive experiences that tend to increase cognitive load.	[14]
Minimize distractions	Design the XR application to minimize distractions and interruptions allowing learners to fully engage in the learning activity.	[36] [8]
Monitor Effectiveness	Gather feedback from learners throughout the development process to ensure that learning outcomes are being achieved and learner needs are being met; revise as needed	[2]
Privacy	Design XR applications that do not collect, store, or share personal information.	[35]

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