Towards a More Inclusive and Engaging Virtual Reality Framework for Social Learning Spaces

By

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A thesis submitted to the Faculty of Graduate and Postdoctoral Affairs in partial fulfillment of the requirements for the degree of

Doctor of Philosophy in Information Technology

in

The School of Information Technology

Carleton University
Ottawa, Canada

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Anthony Scavarelli
Acknowledgements

Thank you, Dr. Arya and Dr. Teather, for your leadership and support.
Thank you, committee, for your time and feedback.
Thank you, Amy, for your love and patience.
Thank you, Henri, Eleanor, and Juno, for your creativity and inspiration.
Thank you, Mum and Dad, for your perseverance.
Thank you, Sherryl, Angie, Linda, Jenny, Katie, Hana, family and friends, for your advocation.
Thank you, collaborators, for your expertise.
Thank you, participants, for your feedback.
Thank you, administration, for your understanding.
Thank you, enthusiasts, for your excitement.
Thank you, students, for your perspectives.
Thank you, creatives, for your imagination.
Thank you, for not letting go.
Thank you, for providing that spark in the darkness.
Thank you, for your honesty.
Thank you, for your reality.
Thank you, for the show.
Preface

The candidate has published several papers during his doctoral studies. Most are cited as foundational papers for chapters in this thesis. In contrast, others have been cited within the chapters (e.g., evaluating how we share physical space with others [311] and conducting remote VR research [184]). Others not cited here are progressing towards publication (Chapters 3 and 5). Additionally, within appendices IV and V, the poster designs for the papers detailing collision avoidance strategies in shared VR spaces [311] and detailing an early form of the Circles framework [308] are also shared. Chapters two to five include the full related papers as published or submitted, with the formatting changed for consistency throughout the thesis.

<table>
<thead>
<tr>
<th>Thesis</th>
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<th>Citation (if available)</th>
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Indirectly related to the thesis


Contributor, 3rd author


Statement of Personal Contribution

The candidate, Anthony Scavarelli, has written all, apart from a peripherally related paper on remote studies in VR, which he contributed as a third author. The advisors, Dr. Ali Arya and Dr. Rob Teather provided guidance and editing. The collaborators from Chapter 5 provided expertise as subject matter experts for the women in trades challenges and inclusion and diversity strategies in colleges. The candidate completed all development work on Circles framework, as well as the design and development of multiple Circles’ worlds, e.g., the example worlds and campfire described in Chapter 3, the research room for conducting remote synchronous lab studies described in Chapter 4, and the women in trades worlds described in Chapter 5. For the other worlds created, e.g., the Kinematics worlds, the candidate helped supervise the development and provided technical support. All research studies were designed and run, along with all data collection and analysis, by the candidate under the supervision of Dr. Ali Arya and Dr. Rob Teather.
"All is dream, all is illusion; I am your vision as you are mine."

Stanley G. Weinbaum,
Pygmalion's Spectacles (1935).
# Table of Contents

**ACKNOWLEDGEMENTS**

**PREFACE**

**STATEMENT OF PERSONAL CONTRIBUTION**

**TABLE OF CONTENTS**

**FIGURES**

**TABLES**

**ABSTRACT**

**CHAPTER 1: INTRODUCTION**

1.1 Motivation .......................................................................................................................... 3
1.2 Problem Statement and Research Objectives ...................................................................... 4
1.3 Research Approach .............................................................................................................. 7
1.4 Contribution ........................................................................................................................ 9
1.4.1 Parallel Studies ............................................................................................................. 10
1.5 Thesis Structure ................................................................................................................ 10

**CHAPTER 2: VIRTUAL REALITY AND AUGMENTED REALITY IN SOCIAL LEARNING SPACES: A LITERATURE REVIEW**

2.1 Introduction ......................................................................................................................... 13
2.2 Problem Statement and Contribution ................................................................................. 13
2.3 Method ............................................................................................................................... 14
2.4 What is VR and AR? .......................................................................................................... 15
2.5 Immersion, Presence, and Embodiment ............................................................................ 16
2.6 Interaction Methods .......................................................................................................... 17
2.7 Interaction Methods Between VR and AR ........................................................................ 18
2.8 Educational Context for VR/AR ..................................................................................... 19
2.8.1 Overview of Related Pedagogy and Theory ................................................................ 19
2.9 Using a VR/AR Platform in Learning ............................................................................. 23
2.10 Prior Work into VR/AR Learning Platforms ................................................................... 24
2.10.1 Familiar Environments Using VR/AR in Learning ..................................................... 26
2.10.2 Learning Platform Technology in Education ............................................................. 27
2.10.3 The Classroom .......................................................................................................... 27
2.10.4 E-Learning ................................................................................................................ 29
2.10.5 Museums .................................................................................................................... 30
2.10.6 Simulation for Training ............................................................................................ 30
2.10.7 Transformative Learning ........................................................................................... 31
2.10.8 Socio-educational VR/AR Platform .......................................................................... 31
2.11 Discussion ......................................................................................................................... 34
2.11.1 Consideration of Technological Limits ...................................................................... 34
2.11.2 Not a Replacement ...................................................................................................... 35
2.11.3 Conflicting and Ambiguous Results ........................................................................ 35
2.11.4 Importance of Embodiment .................................................................................... 36
2.11.5 Accessibility ................................................................................................................. 37
2.11.6 Content Creation ....................................................................................................... 38
2.11.7 VR versus AR ............................................................................................................ 38
2.11.8 Challenges of Implementing VR/AR in the classroom ............................................. 39
Figures

FIGURE 1. ILLUSTRATING THE PATHWAY FROM RESEARCH OBJECTIVES TOWARDS RESEARCH QUESTIONS THAT INCLUDE THE DESIGN, DEVELOPMENT, AND EVALUATION OF OUR PROPOSED FRAMEWORK. ................................................................. 8

FIGURE 2. CAMPFIRE HUB, LEFT, WITH THE CAMPFIRE OFF, AND CENTRE, WITH THE CAMPFIRE TURNED ON. ALSO, NOTE THAT THE THREE SPHERICAL PORTALS NOW APPEAR IN THE BACKGROUND ALLOWING USERS TO CLICK AND TRAVERSE TO OTHER VIRTUAL LEARNING ENVIRONMENTS (VLES). ON THE RIGHT ARE THREE DIFFERENT USERS WITH NAME AND PLATFORM-TYPE LABELS. ................................................................. 53

FIGURE 3. HIGHLIGHTING THE RELATIONSHIPS BETWEEN AN INDIVIDUAL (AVATAR IN THE VR SPACE), A GROUP (A COLLECTION OF AVATARS THAT CAN SEE AND INTERACT WITH EACH OTHER), AND A CIRCLE (A GROUP OF AVATARS VISITING ONE OR MORE CIRCLES' WORLDS/VLES). .......................................................... 56

FIGURE 4. AN EXAMPLE OF HOW LEARNERS WITHIN THE SAME CIRCLE CAN SEE EACH OTHER AND SHARE ARTEFACTS FROM DIFFERENT WORLDS (NOTE THE HOMEWORK ARTEFACT FROM THE WORLD ON THE RIGHT IS ALSO PRESENT IN THE CAMPFIRE WORLD ON THE LEFT WHILE BEING HELD). ................................................................. 58

FIGURE 5. FROM LEFT TO RIGHT, SYMMETRIC SINGLE-SELECTION INTERACTIONS ARE SHOWCASED ON DESKTOP (MOUSE CLICK), MOBILE (FINGER-TAP), AND HMD (CONTROLLER TRIGGER-CCLICK ON RAY CAST SELECTION). ................................................. 60

FIGURE 6. BASIC SYMMETRIC SELECTION-BASED INTERACTION OBJECTS, FROM TOP-LEFT TO BOTTOM-RIGHT: INTERACTIVE OBJECTS TO TRIGGER EVENTS, TELEPORT CHECKPOINTS, CIRCLES' ARTEFACT (SELECT TO PICK-UP, AND USE BUTTONS BELOW TO MANIPULATE AND RELEASE), HYPERLINK PORTAL TO ANOTHER VLE, A SIMPLE “CIRCLES-BUTTON” TO TRIGGER ANOTHER EVENT, AND A HAT “COSTUME” OBJECT TO CHANGE AVATAR APPEARANCE. ................................................................. 61

FIGURE 7. CIRCLES' CLIENT-SERVER SYSTEM ARCHITECTURE. THE JAVASCRIPT SERVER SERVES BOTH 2D AND 3D/WEBXR PAGES, AND THE CIRCLES API ADJUSTS SELECTION AND NAVIGATION TYPES DEPENDING ON THE PLATFORM THE CONTENT IS BEING SERVED TO. NOTE THAT UNDER SELECTION, PRESENTATION, AND NAVIGATION, DVR IS DESKTOP VR, MVR IS MOBILE VR, AND HVR IS HMD VR. THOUGH CIRCLES IS BUILT ON EXISTING FRAMEWORKS SUCH AS A-FRAME (GENERAL WEBXR LIBRARY), NODE.JS (SERVER), AND MONGODB (DATABASE), WE WILL SEVERAL CIRCLES API, COMPONENTS, VLES, VLAS, AND INTERACTIONS TO JOIN ALL THESE SYSTEMS TOGETHER FOR MORE INCLUSIVE SOCIAL LEARNING IN VR. ........................................ 64

FIGURE 8. DEVELOPERS CREATED THREE CIRCLES' WORLDS TO DESCRIBE VIOLA DESMOND'S STORY. ........................................................................................................ 69

FIGURE 9. DEVELOPERS CREATED THREE CIRCLES' VLES TO HIGHLIGHT THE CHALLENGES WOMEN MAY FACE IN THE TRADES. ............................................................................. 70

FIGURE 10. DEVELOPERS CREATED THREE DIFFERENT CIRCLES' VLES TO HELP INTRODUCTORY PHYSICS STUDENTS UNDERSTAND BASIC KINEMATICS. ............................. 70

FIGURE 11. FROM LEFT TO RIGHT, THREE STUDIES USE CIRCLES TO CREATE A SYMBOLIC MEMORY PALACE FOR AN INTRODUCTORY COGNITIVE SCIENCE COURSE, A COMMUNITY CO-DESIGN STUDY WITH A LOCAL INDIGENOUS GROUP, AND A VIRTUAL RECREATION OF A UNIVERSITY CAMPUS. ........................................................................................................ 71
FIGURE 12. SEVERAL STUDENT PROJECTS USED CIRCLES TO CREATE VIRTUAL LEARNING EXPERIENCES CENTRED AROUND THE THEMES OF SPACE TRAVEL, VR HISTORY, AND AI HISTORY. ................................................................. 72

FIGURE 13. DEVELOPERS CREATED SEVERAL CIRCLES VLEs FOR EXAMPLES AND RESEARCH. FROM LEFT TO RIGHT, AN "EXAMPLE WORLD" SHOWCASING CIRCLES' COMPONENTS, AN "EXAMPLE NETWORKING WORLD" SHOWCASING CIRCLES' NETWORKED COMPONENTS, AND A SELECTION AND SEARCH "RESEARCH WORLD." ..... 73


FIGURE 15. THE CIRCLES FRAMEWORK'S "WOMEN IN TRADES" ELECTRICIAN'S SCHOOL LAB RUNS ON GOOGLE CHROME (DESKTOP) FROM A PARTICIPANT'S PERSPECTIVE. THESE IMAGES SHOW TWO VIRTUAL ARTEFACTS, SAFETY GLOVES, A CLIPBOARD, AND A DRILL. USERS LEARN MORE ABOUT CHALLENGES IN LEARNING SPACES BY SELECTING A VIRTUAL LEARNING ARTEFACT (VLA) AND FINDING MORE INFORMATION VIA AUDIO AND TEXT NARRATION AND OBJECT MANIPULATION VIA THE THREE-BUTTON SELECTION-BASED UI UNDER THE ARTEFACT. ............................................................. 83

FIGURE 16. THE MOST COMMON FORMS OF FITTS LAW SELECTION STUDIES (LEFT) UTILIZE A SIMPLE POINTER DEVICE, AND THE USER SELECTS THE CENTER VERTICAL TARGET, MOVES FROM ONE SIDE TO THE NEXT, AND BACK AGAIN FOR N NUMBER OF TRIALS. THE 2D FORM (CENTRE) ASKS THE USER TO SELECT TARGETS NUMBER 1, THEN 2, AND SO ON FOR N TRIALS WHERE THE USER CAN MOVE IN BOTH THE VERTICAL AND HORIZONTAL DIRECTION. THE 3D VERSION (RIGHT) IS SIMILAR TO THE 2D VERSION BUT REQUIRES A POINTER DEVICE, I.E., A LASER POINTER. DUE TO THE USE OF A "LASER/RAY-CASTING" POINTER, THE ANGULAR (ROTATIONAL) DISTANCE (DEG) IS USED TO DETERMINE THE WIDTH OF TARGETS (Ω) AND DISTANCE BETWEEN TARGETS (Α). THIS STUDY USES 2D AND 3D FORMS. ............................................................................................................... 85

FIGURE 17. A TIME-BASED FLOWCHART OF OUR THREE-EXPERIMENT STUDY. ................. 90

FIGURE 18. LEFT: THROUGHPUT (BITS PER SECOND) BY VR PLATFORM. ERRORS BARS SHOW ± 1 SD.] RIGHT: LINEAR REGRESSION MODEL FOR ALL VR PLATFORMS, SHOWING THE RELATIONSHIP BETWEEN ID AND MT. ........................................................................ 94

FIGURE 19. SEARCH TIME (MILLISECONDS) BY VR PLATFORM. ERRORS BARS SHOW ± 1 SD. .................................................................................................................................... 94

FIGURE 20: IMAGE OF OUR ITERATIVE DESIGN PROCESS FOR CREATING VIRTUAL REALITY LEARNING CONTENT. ................................................................................................. 108

FIGURE 21: OVERVIEWING ALL THE VLEs AND VLAs DESIGNED AND IMPLEMENTED IN OUR VR LEARNING ACTIVITY. AT THE TOP IS THE “GROWING UP” VLE WITH THE (STARTING FROM LEFT TO RIGHT, TOP TO BOTTOM) MATH HOMEWORK, PARENT’S SHOP
KEYS, AND ACCEPTANCE LETTER VLAS. THE “IN THE CLASSROOM” VLE WITH SAFETY GLOVES, DRILL, AND INSTRUCTOR’S CLIPBOARD ARTEFACTS ARE IN THE MIDDLE SECTION. AT THE BOTTOM IS THE “ON THE JOB” VLE, WITH THE STEPPING LADDER, LUNCH BOX, AND FAMILY PHOTO ARTEFACTS. REFER TO TABLE 1 FOR MORE DETAIL ABOUT EACH VLE AND VLA. SEE TABLE 10 FOR MORE DETAIL ON EACH VLE AND VLA AND WHICH THEMES INSPIRED THEIR CREATION.

FIGURE 22: THE CAMPFIRE – THIS VLE ACTS AS A “HUB” FOR CONNECTING THE THREE CIRCLES’ “WORLDS” OR VLES USED IN THE WORKSHOP VIA SPHERICAL “PORTAL” HYPERLINKS THAT ALLOW PARTICIPANTS TO CLICK AND TRAVEL TO EACH RESPECTIVE VLE. EACH PORTAL HYPERLINK INCLUDES PROMPT QUESTIONS BELOW TO ENCOURAGE DISCUSSION AND REFLECTION ON EACH OF THE VLE EXPERIENCES. THE CAMPFIRE ALSO ACTED AS AN INFORMAL MEETING SPACE FOR PARTICIPANTS TO CONNECT TO DISCUSS VIA CIRCLES’ VOICE CHAT THE VLES THEMSELVES OR TO ENGAGE NATURALLY IN OFF-TOPIC CONVERSATIONS.

FIGURE 23: VISUALIZING THE HIERARCHY OF THE 8 THEMES DISCOVERED WITHIN OUR STUDY WITHIN TWO PRIMARY FACTORS OF INCLUSION AND ENGAGEMENT TO CREATE TRANSFORMATIVE LEARNING. RATHER THAN EXPLICITLY VISUALIZING THE THEMES AS “SKEPTICISM” AND “INTERNAL AND EXTERNAL CHALLENGES,” WE LEAVE THEM AS OVERARCHING ASPECTS TO GUIDE THE FUTURE DEVELOPMENT OF VR AS LEARNING TOOLS.

Tables

TABLE 1: Describing the papers, and corresponding citations, if available, and their relevance to this thesis ................................................................. II
TABLE 2. Pinho et al’s considerations for “usable and useful” cooperative manipulation techniques [276]. ................................................................. 19
TABLE 3. Several VR/AR applications and platforms over the past two decades showing relative functionalities a platform support (HMD, Desktop, and/or mobile etc.) and social interactions context ........................................... 33
TABLE 4. Table describing the basic affordances of VR/AR, building from prior research while also highlighting differences between VR and AR .............. 41
TABLE 5. Some examples of solo/multi-user experiences within either a VR or AR context. ................................................................................................. 41
TABLE 6. Circles’ five guiding principles are inspired by UDL, UD, RBI, and SIM design principles (described within). These align with Circles’ features described in Section 2.3 ................................................................................ 55
TABLE 7. Circles has several core features based on the guiding principles described in Table 6 ................................................................................. 58
TABLE 8. Results for the Selection and Search Studies ...................................... 93
TABLE 9. The qualitative data was analyzed in observation notes and open-ended post-questionnaire questions about the final "VLE Exploration" experiment in this study. First, with an expected set of thematic codes from our literature review (deductive), then adding codes found with data that did not fit easily or were surprising (inductive), we determined 11 central themes. .................................................................................................................. 96
TABLE 10: Themes identified within subject-area research, VLE question prompts and VLA description/narration text .................................................. 110
TABLE 11: Starting with 11 deductive codes gleaned from prior literature and adding 18 more inductive codes found by repeatedly analyzing the qualitative data received, we settled upon 8 final themes after merging and sorting all codes collected. .......................................................................... 122
Abstract

Virtual reality in learning has a significant inclusion problem as the focus on using head-mounted displays and immersive interactions such as motion controls and hand-tracking has become more mainstream. Many immersive virtual reality challenges exist, such as cybersickness, the inability to use physical controls or space, social anxiety, and even conflicting studies on whether head-mounted display virtual reality learning experiences increase learning. Noting these challenges, we should be open to alternative approaches to virtual reality, such as supporting desktop and mobile virtual reality platforms in addition to head-mounted displays. In this thesis, the Ph.D. candidate, Anthony Scavarelli, explores more inclusive and engaging virtual reality in learning by reviewing the current state of the art in virtual reality and learning to propose significant research directions that center on creating more accessible virtual reality activities within social learning spaces (Chapter 2). Based on this work, the candidate developed a multi-platform virtual reality framework called Circles (Chapter 3). Then the candidate evaluated the usability and performance of Circles’ fundamental interactions of selection and search within a simulated lab environment (Chapter 4) and the real-world documented design and evaluation of Circles’ virtual learning environments and virtual learning artefacts within a post-secondary gender diversity workshop, in collaboration with a Canadian College (Chapter 5). This thesis describes the potential of the Circles framework and its underlying theoretical contributions around considering the socio-cultural context of social learning spaces. It suggests that multi-platform socially scalable virtual reality can be a solution to virtual reality’s inclusion problem within social learning spaces.
“The ultimate display would, of course, be a room within which the computer can control the existence of matter. A chair displayed in such a room would be good enough to sit in. Handcuffs displayed in such a room would be confining, and a bullet displayed in such a room would be fatal. With appropriate programming such a display could literally be the Wonderland into which Alice walked.”

Ivan E. Sutherland,
The Ultimate Display (1965).
Chapter 1: Introduction

Creating more engaging and impactful learning environments within our learning institutions, such as post-secondary education (PSE), is a powerful motivator for exploring emerging technology to support more engaged and exceptional learners with essential 21st-century skillsets such as communication, collaboration, and critical thinking [413]. We have seen the rise of multimedia, the internet, and videoconferencing become powerful mainstays for connecting students to their classrooms with technology over the past two decades. And to create more powerful and convenient experiential learning experiences [180], contemporary virtual reality (VR) and augmented reality (AR) has the potential to change our physical classrooms and museums into powerful social learning spaces where users learn together and alone across continually shifting physical and virtual realities, using both physical and digital tools/artefacts to re-create more authentic, engaging, and transformational learning experiences [258, 309]. However, over decades of VR/AR research, we are yet to fully understand how to design and develop virtual learning environments for one-to-many learners that are engaging, inclusive, transformative, and considerate of the socio-cultural context of the learning environments immersive tools may be used within [110]. While it should not be surprising that trying to re-create a reality we do not yet fully understand on a psychological [400], physiological [292], and universal level [182] is immensely challenging, it appears an inevitable objective, as our dreams [213, 278], and stories [387], behold a virtual reality indistinguishable from our physical reality [48, 358], inspiring our current research and development efforts [321]. Still, education should be available to everyone, and thus the future of learning with VR/AR must also be inclusive and engaging.

This thesis acknowledges that VR and AR occupy the same mixed reality spectrum, ranging from entirely virtual to partially virtual to completely real. Within both the literature and industry, we have seen this continuum referred to as either Reality-Virtuality (RV) [235], Extended Reality (XR) [93], or Spatial Computing [133]. The boundary between what is real and what is virtual, and where our physical presence and actions become virtual is becoming increasingly unclear. The categories of physical and
virtual become blurred when we consider the information appliances such as smartphones [91] that most of us now carry in our pockets and that some Head-Mounted Display (HMD) devices now allow both VR and AR modes [131, 154, 227]. Multi-sensory immersive technologies will further manipulate our perceptions of reality, making the difference between reality and virtual reality more difficult to differentiate. Some contemporary philosophers argue that virtual reality, even in its current form, should be treated as reality [48]. However, for the sake of scope in design requirements and keeping focus within a specific area of research, this thesis will discuss VR exclusively for its immersive affordances, though we do note that future work will naturally include forms of similarly designed augmented reality (AR), where VR developers overlay virtuality onto reality, and augmented virtuality (AV), where developers overlay reality onto virtuality. The categories of VR and AR will likely become semantic as the technology expands into various social learning spaces where physical and virtual differences become ambiguous, such as museums where the physical environment, visitors, digital tools, and artefacts are a significant part of the experience [96, 334]. We also consider VR as a broad term referring to a three-dimensional virtual environment (3D VE) which can be accessed through HMD or desktop and mobile apps.

**Social learning Space,**

where users learn together and alone across continually shifting physical and virtual realities, using both physical and digital tools/artefacts to re-create more authentic, engaging, and transformational learning experiences.

![Figure 1. Illustrating how physical and virtual tools, artefacts, and spaces overlap within social learning spaces.](image-url)
1.1 Motivation

As researchers and developers have explored VR over the past several decades, focusing on head-mounted display (HMD) VR more recently, we should consider whether recreating a hyper-immersive HMD virtual reality in learning is truly the most inclusive method of moving forward. Within this context, we refer to **inclusion** as “using proactive measures to create an environment where people feel welcomed, respected and valued, and to foster a sense of belonging and engagement” and **accessibility** as “the combination of aspects that influence a person’s ability to function within an environment” [260]. Whereas **diversity** is “the presence of a wide range of human qualities and attributes within a group, organization or society,” and **equity** is “considering people’s unique experiences and differing situations, and ensuring they have access to the resources and opportunities that are necessary for them to attain just outcomes” [260]. Contemporary HMDs have inclusion and accessibility challenges such as cybersickness [195], physical discomfort [174, 398], social anxiety [41, 298], inherent gender biases [248, 390], and may even make learning more difficult due to higher cognitive load [211, 218, 397, 403]. We must meaningfully approach the problem from diverse perspectives, being mindful of our design decisions to ensure equitable VR use in learning. This more inclusive design approach includes engaging with the communities [303] that will use this technology and piloting, iterating, and testing scalable interactions (from simple to complex) and scalable VR platforms (supporting HMD, desktop, and mobile) to allow us to see potentially unseen possibilities. Ideally, researchers will compile the results into a theoretical and practical framework that makes it easier for others to understand and utilize engaging and inclusive immersive technology design. Exploring such a framework is the impetus of this thesis. By focusing on inclusive and engaging, VR-based transformative learning, i.e., “the expansion of consciousness through the transformation of basic worldview and specific capacities of the self” [85], we aim to avoid the problem of “generalization” [71] and explore the design and development of an inclusive VR learning framework. One situated within socio-cultural learning theory to expand and enhance our existing social learning spaces [88, 251, 346].
1.2 Problem Statement and Research Objectives

This thesis addresses the problem of how we make social learning spaces more inclusive and engaging by suggesting that existing research suggests that VR increases engagement within learning activities, but how to increase VR inclusion is a lesser-understood challenge. There is little research on making VR learning activities more inclusive, and no known framework supports doing so. Specifically, we are looking to increase the inclusion of VR learning activities by combining the individual-focused accessibility guidelines of Universal Design for Learning [222, 365] and Universal Design [365] with more social and collaborative accessibility design principles found in prior reality-based and immersive interactive media [159, 334]. We have created a VR learning framework, Circles, with these guidelines to make developing more inclusive VR learning activities easier.

With a desire for VR to help teach higher-order skills such as critical thinking, communication, and collaboration [237, 413], we identify four research objectives (ROs) significant to the implementation of VR within social learning spaces with a “ground-up” approach whereby we first understand the problem (RO1), then develop a potential solution (RO2), evaluate the usability of the solution (RO3) to limit technical distractions during real-world use, then explore the proposed solution within a real-world social learning space (RO4).

Within the following section (Figure 1), we then connect these ROs to more specific research questions (RQs) that this thesis answers within chapters 2-5.

**RO 1: Understand the state of the art in VR’s educational potential, opportunities, and challenges (Chapter 2).**

The field of using VR in learning is vast. However, even after decades of research, it is still not clear how educators and researchers use VR within social learning spaces beyond that many of VR’s affordances, such as embodiment, presence, and immersive virtual learning environments [66, 302, 309] naturally map with better experiential learning opportunities [180]. However, few researchers have studied accessibility, inclusion, and sociability within the VR learning context. Additionally, most contemporary social VR
efforts focus on HMD VR platforms and presentation features that aim to re-create classroom and conference settings, suggesting there is much to research and explore in better understanding the potential, opportunities, and challenges of VR better to design future VR experiences within social learning spaces.

**RO 2: Developing a VR framework using a socio-cultural pedagogical foundation (Chapter 3).**

Increasingly, researchers suggest emerging technologies such as VR increase learning within social learning spaces such as classrooms due to their experiential affordances [258, 306]. Still, researchers and educators give insufficient consideration to the existing learning theories and methodologies that best guide VR learning approaches [66, 110, 193, 285]. It will be essential to frame all experiential education VR proposals within the landscape of existing learning theories and methodologies that acknowledge the social environments we learn within. Therefore, we propose a VR learning framework within a socio-cultural learning context that observes that the learning material, individuals, others, spaces, artefacts, and tools are interconnected [88, 167, 185]. We are interested in which VR platform a learner may prefer due to differences in usability between various VR platforms, but also which platform a learner may choose due to more inclusive socio-cultural factors such as self-consciousness [41, 298, 313], task [301, 397, 403], gender [248, 390], or learning outcome [211, 397].

**RO 3: To evaluate the performance and usability of simple selection interactions and search that work across desktop, mobile, and HMD VR. (Chapter 4).**

Within the guidelines of universal design, we aim to make “equitable,” “flexible,” “simple and intuitive” interactions [365]. Still, it is unclear how we can make VR more accessible and inclusive using these principles when there is a hyper-focus on immersion using HMD headsets and complex reality-based controls. Any VR learning framework developed must create a simple, scalable interaction system across VR platforms and individual preferences and abilities to support more inclusive VR. Previous multi-platform VR research has shown that users strategically change between VR platforms for learning depending on the task [301, 397, 403]. Yet, currently, the only VR API that
natively supports desktop, HMD, and mobile VR is WebXR [386], and there are few use cases of researchers and developers using the WebXR API to develop VR learning content.

Additionally, there is little empirical evidence comparing the relative performance of all three platforms supported by WebXR (desktop, mobile, and HMD) or if the performance of the individual platforms is in line with non-WebXR studies in VR interaction usability. Technical and usability issues can distract users [90, 403] and reduce performance when using these systems for learning; therefore, the fundamental VR actions within these systems require usability testing before testing for higher-order skills within social learning spaces.

**RO 4: Exploring the design and development of transformative social VR learning activities. (Chapter 5).**

Researchers have noted that “perspective-taking” as a form of empathy – the ability to imagine the perspective of others [28, 361] is a powerful VR learning affordance [28, 149, 187, 323]. Learning to be more empathetic and understand others’ varied perspectives within diverse classroom environments is an essential 21st-century skill, often associated with more significant innovation through critical thought and enhanced collaboration/community [14, 230, 275]. Perspective-taking also aligns with transformative learning whereby problematic frames of reference are made more inclusive, discriminating, open, reflective, and emotionally able to change [228]. Unfortunately, some researchers have suggested that embodying others to encourage empathy - taking on the virtual body of another, not your own - can result in “identity tourism” [250], whereby we act out stereotypes instead of truly understanding that person’s background and motivations [173]. We are interested in whether we can build a framework to enhance perspective-taking using VR without the problematic “identity tourism” found in the virtual embodiment of others. Features that appear to be crucial to encouraging this type of learning are storytelling [112], artefact exploration [171, 207, 251, 355], role play [28], and reflection [28, 164].
Designing and developing engaging and inclusive virtual learning environments is challenging. From a generalist viewpoint, several frameworks can guide use, ranging from general system design that recommends user testing, empirical testing, and iterative design [128, 162] to more universal [365] and inclusive design [325, 414] frameworks to make systems accessible to many users [175, 317]. Re-creating a reality we do not fully understand is an enormous challenge, but understanding this challenge is essential for building compelling and transformative VR learning experiences. Many VR design frameworks [51, 262, 375] focus on various HMD forms, with engagement through immersion a significant factor. Still, few researchers consider inclusion, the socio-cultural context, and transformative learning in their work.

1.3 Research Approach

Due to the interconnected nature of learning - within the learner, between the space and learner [193, 285], including mediating artefacts [88, 251, 346], and between the learner and peers [167] – a mixed methods approach whereby we capture empirical data from both user studies and from real-world case studies, is likely the most thorough way to capture the phenomenology of how learning is happening when using VR. We note that our usage of “usability” extends beyond the individual [256] to include social usability [151, 272, 336]. As our work focuses on using VR within social learning spaces, it must consist of socio-cultural considerations on how this technology is used with others.

We designed our research into four research objectives (ROs): (1) to understand the state of the art in VR’s educational potential, opportunities, and challenges; (2) to develop an inclusive VR framework using a socio-cultural pedagogical foundation; (3) to evaluate the performance and usability of simple selection interactions and search that work across desktop, mobile, and HMD VR; and (4) to explore the design and development of transformative social VR learning activities. Figure 1 visualizes our four primary research objectives that drive several research questions. We describe these research questions and methodology in chapters 2 - 5. Please see the contributions in section 1.4 and the thesis structure in section 1.5 to understand how these research objectives connect to each study and chapter.
<table>
<thead>
<tr>
<th>RO-1</th>
<th>Understand the state of the art in VR’s educational potential, opportunities, and challenges.</th>
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<tbody>
<tr>
<td>RQ 1.1</td>
<td>What is VR, its interactions, affordances, and social context?</td>
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<tr>
<td>RQ 1.2</td>
<td>What is the educational affordances, pedagogy, and examples of learning with VR?</td>
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<tr>
<td>RQ 1.3</td>
<td>What are the challenges and opportunities of VR in learning?</td>
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<tr>
<th>RO-2</th>
<th>Develop a VR framework using a socio-cultural pedagogical foundation.</th>
</tr>
</thead>
<tbody>
<tr>
<td>RQ 2.1</td>
<td>How can we build a VR framework to increase engagement and inclusion within learning activities?</td>
</tr>
<tr>
<td>RQ 2.2</td>
<td>How to make it easier to create VLEs and VLAs that encourage communication, collaboration, and critical thinking within a transformative learning context?</td>
</tr>
<tr>
<td>RQ 2.3</td>
<td>How does using alternative learning methodologies that consider a socio-cultural pedagogy change the foundation for VR design decisions within social learning spaces?</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>RO-3</th>
<th>Evaluate the performance and usability of simple selection interactions and search across desktop, mobile, and HMD VR.</th>
</tr>
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<tbody>
<tr>
<td>RQ 3.1</td>
<td>What are the differences between the desktop, tablet (mobile), and HMD WebXR in terms of selection and search performance, and usability? Are these differences consistent with prior multi-platform VR performance studies?</td>
</tr>
<tr>
<td>RQ 3.2</td>
<td>Does multi-platform WebXR, specifically the Circles framework, show potential for usably supporting learning activities within social learning spaces?</td>
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<tr>
<th>RO-4</th>
<th>Explore the design and development of transformative social VR learning activities.</th>
</tr>
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<tbody>
<tr>
<td>RQ 4.1</td>
<td>What can we learn from the creation of VR VLEs and VLAs to guide future design and development for educators, developers, and researchers?</td>
</tr>
<tr>
<td>RQ 4.2</td>
<td>What are the challenges, opportunities, and surprises in using desktop, mobile, and HMD VR to increase inclusion in real-world VR learning activities?</td>
</tr>
<tr>
<td>RQ 4.3</td>
<td>What does an inclusive VR model look like, that connects how people create inclusive and engaging VR learning activities with how people use them?</td>
</tr>
</tbody>
</table>

Figure 1. Illustrating the pathway from research objectives towards research questions that include the design, development, and evaluation of our proposed framework.
1.4 Contribution

In this thesis, we identify the following challenges for VR use in learning: lack of exploration into making learning with VR more inclusive, a lack of learning theory and methodology background in many VR learning efforts, lack of clarity around how educators use VR for teaching higher-order skills, and the need for more real-world case studies, testbeds, and validation on the assumptions of VR enhanced learning [71]. Our work will further illuminate the benefits of using inclusive VR as a learning tool in social learning spaces such as PSE classrooms while also contributing examples of real-world use-case scenarios and pilot studies.

Succinctly, the contributions offered by this thesis are as follows:

- An expansive overview of the use of VR and AR in social learning spaces and potential avenues of exploration into socio-cultural learning methodologies. This research overview allowed us to uncover novel insights that inspired this research (Chapter 2).

- A theoretical framework that describes how experiential learning in VR can be inclusive and transformative. This framework includes further insight and exploration into the learning theories that better define how educators, developers, and researchers can use VR within socio-cultural contexts (Chapters 2, 3, 5).

- A practical and open-source framework as a tool for developers, researchers, and educators (https://github.com/PlumCantaloupe/circlesxr). And a set of design principles for creating experiential learning in VR that is inclusive and engaging (Chapter 3).

- Further insight into the relationships between VR platforms, social learning spaces, and usability from a socio-cultural context (Chapters 4, 5).

- An empirical study into the performance and usability of multiple VR platforms and the use of WebXR for VR learning endeavours (Chapter 4).
• Real-world case studies exploring social VR as a learning tool for PSE (Chapter 5).

1.4.1 Parallel Studies

Though the candidate is not directly involved, parallel studies are being developed and run in other Carleton University departments using the Circles VR learning framework described in this thesis. For example, in cognitive science, a brain anatomy and function “memory palace” is being developed [31]. Another information technology project explores indigenous technology empowerment [402] and other researchers and developers are creating virtual learning environments for the physics departments and Biology, English, and Canadian/Indigenous Studies.

1.5 Thesis Structure

The thesis’ organization is kept simple by design. As an integrated thesis, there is an introduction (Chapter 1) and conclusion (Chapter 6), but Chapters 2 through 5 are in a self-contained “paper form.” As such, and for the papers’ self-sufficiency, the candidate may repeat some background information within each chapter’s introductions. As described in Section 1.4.3, some are published, while others are in the peer review process. However, though no content has been modified in the paper submissions, the formatting, image resolutions, and headings have been changed to be consistent with the structure of the integrated thesis guidelines.

• **Chapter 1** – Thesis introduction.

• **Chapter 2** – *ROI, understand* the state of the art in educational potential, opportunities, and challenges of VR [309].

• **Chapter 3** – *RO2, develop* an inclusive VR framework for social learning spaces built on a socio-cultural pedagogical foundation [306, 308] [updated full paper in peer review].
• **Chapter 4** – *RO3*, evaluate the performance and usability of simple selection interactions and search across desktop, mobile, and HMD VR [307].

• **Chapter 5** – *RO4*, explore the design and development of transformative social VR learning activities [paper in peer review].

• **Chapter 6** – Thesis conclusion.
"I was immediately obsessed with the potential for multiple people to share such a place, and to achieve a new type of consensus reality, and it seemed to me that a ‘social version’ of the virtual world would have to be called virtual reality."

Jaron Lanier,
Chapter 2: Virtual Reality and Augmented Reality in Social Learning Spaces: A Literature Review

This chapter has been published (or submitted) as a journal (or conference) paper:


2.1 Introduction

Virtual Reality (VR) and Augmented Reality (AR) technologies are currently receiving a great deal of attention, thanks in large part to the commercial availability of new immersive VR/AR platforms [231, 264] and lower-cost standalone VR/AR platforms such as the Oculus Quest [263]. Additionally, frameworks are quickly appearing to make VR/AR development easier for the web [7], through plugins into popular game engines [348], and with the technology built directly into the operating systems of mobile platforms [16]. While these technologies first appeared in research and development dating back to middle of the 20th century [20, 219] there is tremendous human interest in the concept of simulating reality which can be seen within fiction as early as the 1930s [387], and much earlier within the philosophical realm, when humans started to consider whether our perceived reality is an “absolute” reality, rather than merely “shadows on a cave wall” [278], “a dream” [72] or a robust “computer simulation” [34].

Current lower-cost and higher fidelity VR/AR technological developments such as increased resolution, reduced latency, and higher framerates have raised hopes for more mainstream and diverse applications within the fascinating area of simulating and augmenting/enhancing reality, in which we are no longer bounded by physical spaces and the physics of the known universe. We are seeing an explosion of experimentation and development of novel applications within VR/AR forms such as gaming [169, 279, 347], film [69, 127], social communities [246, 293, 379]; and, most interestingly for this survey, educational endeavours [70, 81, 135, 171, 302, 314].

2.2 Problem Statement and Contribution

Though many educational endeavours use technology to make learning more motivating and effective, and the use of VR/AR in education is not new, there are many facets of
VR/AR use that could be improved. Specifically, there is ambiguous evidence of effective learning gains using VR or AR technologies [66, 110] or that generalizing results has many caveats [71, 224], minimal focus on theoretical backgrounds grounded in learning theory [66, 110], minimal research into combining VR and AR, and very few explorations into how we better acknowledge the social properties of social learning spaces where we interact together in co-located areas such as classrooms and museums. Succinctly, the areas covered by this review follow.

- Multi-user, specifically closely coupled (collaborative), VR/AR theory, and interaction.
- Responsive, multi-platform VR/AR content that adjusts functionality, interaction input, and display output depending on the platform accessing the content. This adaptivity aligns with Universal Design for Learning [299] methodologies for increasing the accessibility of learning materials.
- The use of VR and/or AR in social, educational contexts such as the more formal classroom and informal educational institutions such as museums.
- Suggested learning theories that may provide for more complete reflections of how learning happens in social learning spaces, with greater consideration of how the embodied, social, and spatial environments affect learning.

2.3 Method

This literature review is a broad and qualitative overview of the use of VR and AR within a social education context, serving as an entry point into a discussion and more sophisticated analysis into the present and near-future of VR/AR in learning. To minimize the size and scope of a paper with such an overwhelming amount of literature on this subject we focused on building upon prior surveys [58, 66, 82, 112, 302, 323] then expanding upon the gaps found in social interactions within VR/AR, the considerations of VR and AR combined into the same educational framework and platform, and how VR/AR in education could be more accessible through multi-platform implementations.
Additionally, to bring more recent literature into this survey, which was predominantly completed in late 2018, and to address some of gaps noted since then, we also build upon the use of HMD VR in the classroom learning spaces [340], as it has been suggested that few classroom studies evaluate HMD VR [216], and embodied design principles in VR and learning [165]. With these key papers, we then applied a snowball method following papers cited within articles until no new relevant articles were identified. Where possible, we also used more focused keyword searches using the terms “education, learning, multi-user, social, museum, virtual reality, augmented reality, mixed reality” within Google Scholar, IEEE, and ACM databases.

2.4 What is VR and AR?

While VR and AR share many similar technologies, such as various tracking sensors and displays, they represent two different approaches in blending the physical and virtual world realities. VR and AR are defined as the following:

- **Virtual Reality (VR):** “an artificial environment which is experienced through sensory stimuli (such as sights and sounds) provided by a computer and in which one's actions partially determine what happens in the environment” [162, 226].

- **Augmented Reality (AR):** “AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it.” [20].

AR traditionally overlays digital content onto a live view of the environment, often as a camera view with mobile platforms, or a see-through display, as found in wearable AR platforms such as Microsoft Hololens [231]. VR technology, conversely, aims to immerse users within a completely artificial environment with various forms of technology to address one or more senses. HMD VR is often referred to as Immersive Virtual Reality (IVR) by providing a stereo display, spatial audio, and controllers (or hand-tracking) for interactions and haptic feedback; but there are many other forms of VR with varying degrees of immersion such as handheld displays and projected walls, in addition to HMDs [43].
Both VR and AR fall subjectively on the Reality-Virtuality (RV) continuum first proposed by researchers Milgram et al. [235]. In this continuum, “reality” lies at one end, and “virtuality” (VR) lies at the other, with Mixed Reality (MR) displays placed between, which denote a category of displays which represent a blending of reality and virtuality to varying degrees. There have also been recent attempts to rename the entire RV continuum as XR (Extended Reality) [93] or “Spatial Computing” [133] to denote all MR platforms and the edge cases of complete Virtuality (immersive VR) and Reality, but to avoid confusion in this paper, we will adhere to the less ambiguous descriptions of VR and AR.

2.5 Immersion, Presence, and Embodiment

The degree to which an individual accepts that a virtual world is real is generally referred to as presence and is an important part of bringing an individual into a virtual space. Note that the terms presence and immersion are sometimes used interchangeably, but most now accept the following definitions. Additionally, we define embodiment below, as it and presence are referred to as the “two profound affordances of VR” [165]:

- **Immersion**: what the technology delivers from an objective point of view. The greater the number of technologies that cover various sensory modalities, in relation to equivalent human real-world senses, the more that it is immersive [39]. For example, just a 2D display is less immersive than a stereoscopic display that tracks head movement.

- **Presence**: the point at which an individual begins to accept an artificial reality as reality. It includes two main illusions to be accepted - (1) the place illusion (that where they are is actually real) and (2) the plausibility illusion (that what is happening is actually happening) [330].

- **Embodiment**: describes the mental representations of the body within space - which can be physical and/or virtual. The three main components of embodiment are (1) body ownership (sense that the body inhabited is one’s own), (2) self-location (being in the place where one’s body is located), and (3) agency (that an
individual can move and sense their own body) [33]; and are considered an integral part of learning [165].

Zimmons and Panter find that making worlds more photorealistic does not necessarily increase presence [410], and Jerald suggests that complete presence is reached by focusing on world stability, depth cues, physical user interactions, cues of one’s own body, and social communication [162]. Additionally, there are several trade-offs such as how closely do the visuals match reality (representation fidelity), how closely do the interactions match reality (interaction fidelity), and how closely the perceived experiences match reality (experiential fidelity) to consider when developing VR applications [162]. Note that for some, with more immersive VR HMDs, some may become nauseous. This is often called cybersickness [195, 220], and likely due to perceived differences between the spatial orientation of the VR visuals and the spatial orientation of the body’s balancing system called visual-vestibular conflict (VVC) [10]. Cybersickness appears to be aggravated by VR experiences that are more action-oriented and individuals that do not have a predisposition to high adrenaline sports [136].

### 2.6 Interaction Methods

Bowman and Hodges define interactions within Virtual Environments (VEs) as concerned with three main task categories: viewpoint motion control (navigation), selection, and manipulation [38]. Furthermore, these selection and manipulation techniques can be classified into six interaction metaphors. LaViola et al. describe these metaphors as grasping (e.g., using a virtual hand), pointing (e.g., ray-casting), surface (e.g., using a 2D multi-touch surface), indirect (e.g., ray-cast select then perform additional multi-touch gestures to modify without directly selecting the object of interest), bimanual (using two hands to interact), and hybrid (interaction technique changes depending on context of selection) [194].

Additionally, the consideration of social interactions in VR/AR is important as there are learning methodologies such as “Together and Alone” [164] and Computer-Supported Collaborative Learning [346] espouse closely coupled collaborative interactions for enhanced learning. Interestingly, some of these collaborative dynamics can be framed
within a social interdependence model (positive = collaborative, negative = competitive) where “the accomplishment of each individual’s goals is affected by the actions of others” [163]. This type of “closely-coupled collaboration” [118] is evident in works such as Schroeder et al.’s “Rubik’s Cube puzzles” [315], the narrative-based constructionist works of the NICE project [300], the several observations on how collaborative manipulation can happen within VR/AR environments [8, 118, 276]. Additionally, the virtual gazebo building project by Roberts et al. broke down tasks into sub-tasks that required multiple users to complete concurrently in both “distinct attribute” (e.g., one holds a wooden beam and the other screws a hole) and “same attribute” (e.g., both users need to pick up an object that is too heavy for one) tasks [295]. These categories of distinct and same attributes are further broken down into also including asynchronous (sub-tasks completed sequentially) and synchronous (sub-tasks completed concurrently) tasks by CVE researchers Otto et al. [268].

Pinho et al. also expand upon this CVE framework by including four considerations when developing a virtual environment for collaboration [276] – see Table 1. These considerations echo similar principles we see within defining Reality-Based-Interaction (RBI) (i.e., considerations for naïve physics and body-awareness & skills for RBIs [159]) and social immersive media (i.e., considerations for socially scalable and socially familiar interactions [334]).

2.7 Interaction Methods Between VR and AR

Collaboration is not limited to users of the same medium (e.g., just VR or AR). Though research is limited within an educational context, there is some interesting work on the use of VR and AR Collaborative techniques. Grasset et al.’s studies point towards negligible effects on task performance and note interesting possibilities whereby the environment provides physical interaction affordances with the use of AR and VR for collaborative tasks [130]. Unfortunately, this study does not seem to sufficiently answer whether some tasks are better suited to VR or AR and what are the effects of technology limitations. There are many instances of digital technology, granting each user a unique view as a positive affordance in multi-user interactions [332]. Additionally, cognitive
load can become an issue in varying perspectives as seen Yang and Olson’s paper studying the use of egocentric and exocentric views in collaborative tasks - “One lesson learnt is that it is harmful to correlate views across sites in a way that requires real-time effortful mental operation such as mental rotation” [399].

There has also been some exploration into users collaborating at different scales in Multiscale Collaborative Virtual Environments (mCVEs) [408], and though the “VARU framework” [157] only uses with AR and projection VR, it opens up some interesting discussion on how objects could have different descriptions (or “extensions”) in each VR or AR space. In learning, there are fewer examples, though there is some promising work that explores how a virtual museum could emulate the social experience of visiting a physical museum by allowing learners to interact with virtual artefacts with VR or AR together [200]. Interestingly, Li et al. note that learners were interested in additional interactions that could be completed together beyond seeing each other’s artefacts moving in the VE, and that unintentional collaboration happened when the AR experience could rotate a model that the VR experience could not, and they had to work together to share information [200].

Table 2. Pinho et al’s considerations for “usable and useful” cooperative manipulation techniques [276].

| Awareness | Showing to one user the actions their partner is performing. |
| Evolution | Building cooperative techniques as natural extensions of single-user techniques, in order to take advantage of prior knowledge. |
| Transition | Moving between single-user and a collaborative task in a seamless and natural way without any sort of explicit command or discontinuity in the interactive process, preserving the sense of immersion in the VE. |
| Reuse | Facilitating the implementation of new cooperative interaction techniques, allowing the reuse of existing code. |

2.8 Educational Context for VR/AR

2.8.1 Overview of Related Pedagogy and Theory

There are several learning theories often used to describe educational technology contexts. Merriam et al. categorize current learning theories as behaviourism, humanism,
cognitivism, social cognitive theory, and constructivism [225]; but it is also worth considering learning theories that better acknowledge the interconnected and complex relationships we have with both the physical and digital environments such as connectivism [327] and paradigms founded by activity theory such as CSCL [345] and Expansive Learning [88]. The selected learning theories that represent existing and potential foundations of learning within VR/AR social learning spaces, follow.

- **Constructivism**: Merriam et al. describe constructivism as a collection of perspectives, all of which share the common assumption that learning is how people make construct meaning from their experience [225]. This theory focuses on the importance of learners actively constructing their knowledge via a more experiential model. Dewey referred to this as “genuine education” [74], Vygotsky highlights that “this process is a social process mediated through a culture’s symbols and language”[225, 380]. Additionally, constructivism is generally considered crucial to self-directed learning [409] and to Lave and Wenger’s concept of situated learning, which suggests that the environment helps to inform learning in individuals [193, 225]. One of the better known experiential learning processes is Kolb’s learning cycle, which defines learning in four steps - concrete experience, reflective observation, abstract conceptualization, and active experimentation [180].

- **Social Cognitive Theory**: proposed by Bandura to consider both the social and personal effect on individual activity and motivation [22]. Schunk defines Social Cognitive Theory as learning that occurs within a social environment – through observation and emulation of others. That by observing others and validating our efforts by their reactions we learn [316]. It is an essential consideration for any social VR systems as it helps us better understand how the social context can both help and hinder learning within the individual.

- **Connectivism**: focuses on the concept that all learning occurs in a network, a connection of entities, within not merely the learner’s mind but also external nodes, such as “non-human appliances” (i.e., smartphones and the web). Siemens
defines connectivism as driven by the understanding that decisions are based on rapidly altering foundations, that new information is continually being acquired and processed, and that the ability to draw distinctions between important and unimportant information is vital [327]. Though not yet accepted as an independent theory, some psychologists refer to its concepts as compatible, in conjunction, with existing learning theories [26].

- **Computer-Supported Collaborative Learning (CSCL):** CSCL is likely an important part of any discussion of the use of VR in social learning spaces, as it is concerned with how learners collaborate using computers [345, 346]. Though CSCL is not explicitly a learning theory when considering the effect of the environment on learning, it is essential to look towards learning frameworks that additionally examine the socio-cultural or socio-historical contexts of social learning spaces [346]. For example, is it culturally acceptable or comfortable to use unfamiliar technology in front of others? These types of questions appear significant, within a VR/AR context, where virtual environments can act as effectors or replacements for our physical learning environments. Addressing this, some CSCL frameworks build on the foundations of activity theory, a German and Marxist framework for describing human activity through a lens that considers the interconnected individual, objectives, community [86, 346] and the cognitive tools or artefacts used to mediate learning such as digital interfaces [251]. Engelström suggests that the application of activity theory to learning provides for a more complete process-based learning alternative to Kolb’s experiential learning cycle [180] and Nonaka and Takeuchi’s four modes of knowledge conversion [259] by more explicitly considering the socio-cultural contexts of social learning spaces and differentiation between instruction and learning [88].

Activity theory is comprised of several key elements – the (1) subject/individual participating in the activity, (2) the object, not tangible like a tool, but rather the “object” of direction that motivates activity, (3) the actions as goal-directed processes to reach the object, and (4) operations as an activity that no longer a goal-directed process, but an
unconscious action required to reach the object [198]. Activity theory allows us to better understand interface interaction as a sequence of actions and processes [64, 186] within constructivist learning environments [167].

Though activity theory is often analyzed concerning an individual, albeit with some input from the surrounding culture and community, there are versions that suggest that social interactions are significant within the learning sciences [87]. For example, instead of merely considering the individual and object [198], Engelström suggests that an activity contains three entities: the individual, the object, and the community within a proposed form of activity learning called expansive learning [86, 88]. Though CSCL is not exclusively concerned with any particular learning theory, those with activity theory foundations, such as expansive learning, remain significant considerations for VR/AR CSCL [346].

In the context of constructivism and experiential learning, it is important that learners can enter real-world situations and “authentic” environments that might otherwise be unavailable to them, due to monetary or physical space constraints. This type of learning is generally referred to as “situated learning,” where learning is situational [345], which could also include socio-cultural aspects. Additionally, this learning can also be mediated through the use of tools (e.g., physical books, maps, or VR/AR) [88, 225, 251]. Contextual learning is what researchers would refer to as near-transfer, “when evaluation is based on the success of learning as a preparation for future learning - researchers measure transfer by focusing on extended performances where students ‘learn how to learn’ in a rich environment and then solve related problems in real-world contexts” [82]. We can also note that memory recollection is closely associated with environment [55, 56, 333], and the power to recreate these “spatial contexts” as virtual spaces (or virtual environments) in VR/AR has great potential to help in the form of virtual “memory palaces” [183]. Not unlike some indigenous groups in Canada and their extraordinary tradition of oral histories that consist of stories passed down the generations - sometimes stories that can only be told “during certain seasons, at a particular time of day, or in specific places” [152].
Within this context, it is also worth mentioning modern teaching methodologies related to social cognitive theory such as “Learning Together and Alone” which focuses on increasing collaborative activities and group processing and reflection to enhance academic achievement [164], and the importance of designing learning materials as consumable by multiple pathways (i.e., a document also being designed to be easily read by text readers) with a “Universal Design for Learning (UDL)” framework [299]. Additionally, with an activity theory lens in VR/AR guided by CSCL, enhanced socio-cultural connections through distributed social activities and various virtual environments can be developed where VR/AR interactions are framed as process-based activities with digital tools (both physical and virtual).

2.9 Using a VR/AR Platform in Learning

Immersive 3D VLE’s allow learners to explore environments and situations that would be impossible to visit in the real world (e.g., the abstract - non-Euclidean geometry, or the physically impossible - the surface of Venus), or even to collaborate at different scales [157] or different VR/AR spaces [129, 131]. This is where digital tools can be of great use in developing Virtual Learning Environments (VLEs) (sometimes referred to as Educational Virtual Environments (EVEs)). VLEs are limited only by the creators’ vision and computer hardware, allowing for significant opportunities for learners to experience situations and environments otherwise inaccessible. Motivation for these digital tools comes from our ability to use embodiment to aid learning via three constructs proposed by embodied learning researchers: (1) the amount of sensorimotor engagement, (2) how congruent the gestures are to the content to be learned, and (3) the amount of immersion experienced by the learner [166]. Epistemic action, described by Kirsh and Maglio as “physical actions that make mental computation easier, faster, or more reliable” [176] also suggest great potential for using digital tools in learning, enhancing arguments connectivism [327] and the ability for digital tools to expand learning possibilities. This concept can be seen as an extension of embodied cognitivism that our bodies (or perceived bodies in the case of the “Proteus Effect”[400], can influence our minds. Some work even suggests that this body transfer can be effective with non-human avatars [351]! Most interestingly are the forms of embodied cognition, categorized by Wilson [392],
that offer symbolic off-loading onto the environment, similar to connectivism, and situated cognition, that deals with spatial cognition within the context of real-world environments [392]. We can quickly see how VR/AR could utilize controls, such as motion controls, and avatar representation within the VE to help learners through the environment and thus triggering cognitive processes that help influence and enhance their learning.

2.10 Prior Work into VR/AR Learning Platforms

With some previous reviews of the literature into 3D VLEs, it is generally considered that most research in this area does not build strong enough off of learning theories, where if any learning theory is cited, it is often one of constructivism [66, 110]. In this review, we aim to build off the foundation of constructivism to also include social cognitive theory and CSCL as a significant addition to the arguments for the use of VR/AR in education. The potential is large for digital technologies, such as VR/AR, to help recreate traditional learning experiences in both self-directed and social settings.

VR/AR can help create more immersive and experiential learning opportunities by encouraging self-learning via tangible and immersive construction tasks, not possible within current Learning Management Systems (LMSs). Additionally, the concept of context within situated learning/situated cognition theory, or more specifically the wide variety of possible settings in VEs, is strengthened when we can share these experiences with students’ peers to further enhance the effect of individuals share and learn from each other [388], propagated by theories of social cognitivism. The ability to jump from one environment and context to another, as virtual near-instantaneous field trips, is a powerful motivator for pursuing the use of VR/AR in education – and these “field trips” within VLEs [37] need not be based in reality. VR/AR allows for a more immersive exploration of abstract concepts such as electromagnetism, Newtonian dynamics, or molecular attachments [302]. Additionally, “the potential advantage of immersive interfaces for situated learning is that their simulation of real-world problems and contexts means that students must attain only near-transfer to achieve preparation for future learning.” [70]
VLE researchers Dalgarno and Lee, extending upon the prior research of Wann and Mon-Williams, define the most significant affordances of these environments, from a learning theory perspective, are [66]:

- **Enhanced spatial knowledge representation**: VLEs can be used to facilitate learning spatially of environments and/or objects.

- **Greater opportunities for experiential learning**: VLEs may increase experiential learning opportunities that not be practical or possible in reality.

- **Increased motivation/engagement**: VLEs increase engagement and motivation in learning.

- **Improved contextualization of learning**: VLEs create more opportunities for learning within a context that better represents how that learning would be used in reality (e.g., learning how to speak publically in a virtual auditorium). Steffen et al. expand on this further by noting that VR/AR affordances may include enhancing positive aspects, reducing negative aspects, and recreating aspects of physical reality [349].

- **Richer/more effective collaborative learning**: VLEs may access the digital mediums for greater collaboration possibilities (e.g., remote participation and innovative multi-user interactions – see section 3.2).

Also, VLE researchers Salzmann and Dede, who often base their VLE research and development around constructivism, suggest the three following affordances of VR technology as most significant [302]:

- **Immersive 3D representations**: VLEs allow for more detailed and richer 3D environments that help to create a greater sense of actually being somewhere else [138][393]

- **Multiple Frames of Reference (FORs)**: Being able to see environments and objects from various points of view helps to learn [89]. Additionally, one could
also add that being able to see the world from others’ perspectives [28] can also be valuable for learning critical thinking, such as challenging ones’ values and beliefs [64].

- **Multisensory Cues:** Using multiple senses (i.e., visual cues, proprioceptive cues, auditory cues, etc.) in learning helps to deepen recall [261][286].

And finally, VLE researcher Shin also notes the following, additional, affordances [323]:

- **Empathy:** Empathy and embodied cognition are two concepts that frequently arise in the discussions of VLE. People can understand and empathize when they comprehend another person’s subjective experience and environment [28].

- **Embodiment:** A virtual body, an analog of the physical body, is used to interact within the virtual environment - an essential part of presence [29, 330] and learning [165].

Yuen et al.’s potential benefits of Augmented Reality in education echo the principles above [405]; but also emphasize on, along with educational AR researchers Dunleavy et al., that AR is a “good medium for immersive collaborative simulation”[81], well suited to social, educational settings.

### 2.10.1 Familiar Environments Using VR/AR in Learning

This section will detail the primary environments in which VR/AR technologies enhance learning effects. This section will not be an exhaustive list of all VR/AR experiences created for pedagogical purposes; but rather a selection of some interesting examples that aim to show the diversity of approaches within both the research and the commercial worlds for social learning spaces, or where there is exciting potential for further development within (e.g., transformative learning within a social context). We will also break down the experiences into “education-type” categories, as some may not be formally acknowledged as educational endeavours.
2.10.2 Learning Platform Technology in Education

Before discussing VR and AR platforms, we should discuss traditional technology platforms in the form of LMSs, currently in widespread use across many post-secondary institutions. They have allowed students and instructors to communicate with each other via textual techniques such as forums, message boards, and email; and have been essential for running online or hybrid classroom-online courses. They also allow students to communicate with each other through forums and private groups; and that this collaboration and communication has been considered invaluable [283]. This type of technology use within classrooms have also led to new kinds of classroom structures such as online-only classrooms, hybrid (a mix of online and face-to-face), and face-to-face classrooms that utilize the concept of the “Flipped classroom,” in which “that which is traditionally done in class is now done at home, and that which is traditionally done as homework is now completed in class,” to help personalize learning for each student [27]. Admittedly though, there is far too little research into flipped classroom effectiveness [4, 30]. However, the recent demand for learner-driven models within formal education contexts lends itself well to further research into how technology such as VR/AR can help augment and accommodate these current “learner-driven” objectives in formal and informal education institutions.

2.10.3 The Classroom

Within the classrooms of grade school and post-secondary institutions, we are seeing VR/AR technologies being used to help educate students, making classes more engaging. One of Google’s VR ventures, Google Expeditions [126], was launched in 2014 to help teachers provide more immersive educational experiences. The instructor passes out smartphones to students for use within Google VR Cardboard headsets, and the students are transported to 360 videos of environments, chosen by the instructor via the tablet. Additionally, InMediaStudio provides a similar system to Google Expeditions for classroom use; but with additional interactive content [83]. There are ongoing explorations into the use of VR and VLEs to create more opportunities for “innovation education” that will promote ideation and innovation skills within the national curriculum.
in Iceland [367], and some early research into exploring supporting multiple non-immersive and immersive VR platforms for content delivery [308]. Within social learning, researchers are also exploring collaborative content creation and virtual note-taking for better retaining knowledge [132].

Thorsteinsson and Denton feel that VLE’s are incredibly relevant to education pedagogy – namely “Constructivism, Computer Supportive Collaborative Learning (CSCL) and Computer-Mediated Communication (CMC)” [367]. The use of computers in a social setting (i.e., the classroom), the construction of tangible pieces, and playing a role (i.e., as the avatar) within VLE’s lends itself well to VR/AR technology use within the classroom.

Research has also been completed by Kerawalla et al. into using AR for teaching science to primary school students [170], using a “virtual mirror” (a screen that displays a live camera feed of the student with 3D content overlaid into the scene) to allow children to manipulate a model of the Earth-orbiting the sun. The researchers observed that their findings “support previous work that explored the use of both VR/AR … where the focus has been on designing environments that students can manipulate and explore promoting inquiry-based learning”. Bodén et al. also created an AR system, called “Save the Wild,” that uses a similar virtual mirror system to allow primary grade students to track origami creatures the students created within a VE [32]. Liarokapis and Anderson also explored the use of AR to help university students better understand engineering concepts, finding that AR is useful when used in parallel with traditional methods [201]. Du and Arya [80] also proposed the use of an HMD AR system as a single screen to replace the personal computer screen and large screen in classrooms. They suggest that such an approach can help reduce distraction and investigate various methods of content control, by the teacher, student, or the system.

There are also several Universities with medical education facilities exploring how to teach anatomy to students better, as the material can be difficult for students to retain. Some studies have looked at spatial awareness as the key to learner’s ability to better
contextualize anatomical features; and have explored using VR/AR for more efficient and convenient anatomical model viewing [119, 282].

2.10.4 E-Learning

E-Learning generally refers to companies and individuals that create and sell products dedicated to teaching others about certain subjects via online technology. Research has been completed on building and testing VR systems for E-learning such as Monahan et al.’s “Collaborative Learning Environment with Virtual Reality (CLEV-R)” which explored the use of 3D virtual environments and avatars that allowed multiple simultaneous students and teachers to communicate with each other via text, voice, camera [240]. Interestingly this research team also introduced a mobile version, mCLEV-R, that allowed access to the same information with significantly limited functionality [239]. Avatar representation in these systems is essential as “online learning environments tend to be designed to facilitate disembodied ways of learning and knowing, which is at odds with contemporary epistemological theories that emphasize contextually, embodied knowledge. 3-D VEs have the potential to address this through user representation and embodied action” [66]. The researchers’ system allowed for virtual lectures and for users to be able to teleport to various environments, but it was mostly a recreation of more traditional and physical forms of teaching through desktop and mobile systems. Arya et al. [17] also covered two case studies (ESL and archaeological online courses) involving the use of virtual environments in learning and note several advantages that virtual environments, such as those found in VR/AR, that state that VR may not only allow “people in different locations to interact”; but also gives users access to facilities not available physically, enables activities that are not possible in physical settings, and offers a variety of observation and measurement tools for performance evaluation and improvement.

There are also a few companies looking at using HMD VR to allow for increased virtual immersion, and some expanded tools for using the technology, to more uniquely augment the learning experience. For example, Labster [188] taking their lab training technology and building VR representations using Google Cardboard for increased
immersion [188], and is also working with Ontario to help post-secondary institutions around Ontario set up VR labs [378].

2.10.5 Museums

Museums should also be included within VR/AR learning environments as they explore the use of VR/AR technologies to naturally engage with visitors in public settings, while also fulfilling mandates of imparting knowledge of cultural heritage - “museums now place an emphasis on education that they never did in the past” [97, 355, 359]. Museums are currently dealing with reduced interest and attendance in younger generations, with some advocates suggesting to “make the experience personal and interactive” [215]. This has lead to experiments in using interactive methods such as various forms of VR/AR displays to help draw in and engage younger audiences. Some interesting examples using VR/AR technologies within museum exhibits [79, 189, 334, 359, 369]) often use Reality-Based Interactions (RBI) [159], to create more embodied interactions. There is also research exploring how VR and AR artefact manipulation could help emulate the social experience of visiting the physical museum [200], and explorations into using narrative across both virtual and physical museum contexts [145]. Research by interactive artist Snibbe highlights that developing “social immersive media” installations within museums that “accommodates the public, social, and informal learning that museums champion” [334]. This type of media, arguably an AR form, focuses on RBI interactions that scale for one to many participants and may be useful in future research into social classrooms that focus on learning experiences that require many learners simultaneously using VR/AR technology. The seven principles of “social immersive media” - visceral, responsive, continuously variable, socially scalable, socially familiar, and socially balanced - also appear quite relevant to socio-educational VR/AR contexts.

2.10.6 Simulation for Training

Within various industries, there are efforts to use both VR and AR to prepare individuals for engagement with more expensive, complicated, or potentially dangerous hardware or processes. For example, the use of VR/AR in simulation could include flight simulation
training for complex surgeries [238, 326], military training [172], or athletic conditioning [24]. Often these systems place users into VEs that recreate a real experience or involve AR overlays that help guide users through a situation. Though these areas are beyond the scope of this review, as we are focusing less on specific training applications and highly specialized hardware, they are still worth mentioning for a broader view on the use of VR/AR in learning.

### 2.10.7 Transformative Learning

Learning is more than retaining knowledge or a process, and can also involve critically evaluating held assumptions, beliefs, values, and perspectives - opening learners to mindful change. This is generally referred to as transformative learning [64, 228], and one powerful example of transformative learning is in using VR to better imagine another’s perspective [28], as a form of creating empathy for other individuals, cultures, or even environmental issues [216, 323]. These changes are possible due to VR’s immersive affordances of perceptual illusions [28] such as embodiment [165] and presence [330] that help to create a sense of actually being someone else, or within another environment. For example, researchers have found that VR experiences that place you within the virtual situation of homelessness can help create longer-term empathy for the homeless [204]. Filmmakers have also explored documentary and 360 film-making to place individuals into unfamiliar situations in an attempt to create the “ultimate empathy machine” [149]; or to create a more robust connection to news stories, such as those that cover prison interrogation [187]. It is still a developing area, as it has also been noted that embodying others in VR experiences may also enhance stereotypes rather than reduce them [173], but it presents an opportunity to use VR/AR technology to better connect learners with new and different situations and environments.

### 2.10.8 Socio-educational VR/AR Platform

Within a discussion of VR/AR examples in education, we can also look towards other VR/AR frameworks that, though may not be directly related to education, may hold interesting lessons and system structures that can be relevant to our survey (some of these
have been mentioned previously). For example, industry social VR platforms such as VRChat [379], AltSpaceVR [11], and Mozilla Hubs [246] share several characteristics. These characteristics include avatar visualization, VEs that can be visited by multiple users, various forms of communication, and support of one or more platforms (see Table 2 highlighting these differences). Across each there is a diverse spectrum of visual quality where applications such as High Fidelity focus on higher-end immersive VR hardware such as the HTC Vive [150] on one end; and AltSpaceVR and Rec Room that support several platforms (Desktop, Mobile, and HMDs). These frameworks often support voice communication, gestures via motion controllers, and floating diegetic GUIs for system interactions.

Within Table 2, we have listed a diverse cross-section of the platforms that support social VR/AR of some sort over the past two decades (both in research and commercially). We note that within the last few years, with the resurgence of popularity into immersive VR with commercially available HMD’s, that the motion/6DOF controllers included are now supported in most new VR frameworks. We also note that very few platforms support more than one modality of interaction/display (i.e., only supporting AR or only supporting desktop or immersive HMD VR). The only real exceptions we observe are within AltSpaceVR [11], Rec Room, and Mozilla Hubs that support VR across several platforms - desktop, and mobile, and HMD - or Google expeditions which has two forms that support either VR or AR. Interestingly, these multi-platform, experiences are becoming more common in recent years as attempts to increase participation in social VR experiences has become difficult with just HMD VR, due to HMDs not being as successful as many had hoped thus far [364], leading to platforms such as High Fidelity, that aimed support at higher-end VR HMDs, to be abandoned [142].

The advantage of greater accessibility, combined with the openness of content created for the web, make WebXR [386] – the successor to the non-standard WebVR API [385] - for supporting desktop, mobile, and HMD VR/AR on the web, an attractive platform to build a social VR/AR platform. Additionally, Beck et al. describe an interesting use of a VR single-wall CAVE, which also tracks another group of users from a remote location to provide an example of both remote and co-located “Group-to-Group Telepresence” and
multi-user closely-coupled interactions. Unfortunately, Beck et al.’s apparatus does require a highly specialized setup of depth cameras, projected displays, and a “Spheron” navigation/interaction device [23].

Table 3. Several VR/AR applications and platforms over the past two decades showing relative functionalities a platform support (HMD, Desktop, and/or mobile etc.) and social interactions context.

<table>
<thead>
<tr>
<th>Application</th>
<th>VR</th>
<th>AR</th>
<th>Desktop</th>
<th>Mobile</th>
<th>Multiuser</th>
<th>Collaborative(^3)</th>
<th>Display</th>
<th>Communication</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>NICE [300]</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>CAVE</td>
<td>verbal</td>
<td></td>
<td>1997</td>
</tr>
<tr>
<td>VES [36]</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>desktop</td>
<td>text/voice</td>
<td></td>
<td>1999</td>
</tr>
<tr>
<td>INVITE [35]</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>desktop</td>
<td>text/voice</td>
<td></td>
<td>2001</td>
</tr>
<tr>
<td>C-VISions [52]</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>desktop</td>
<td>text/voice</td>
<td></td>
<td>2002</td>
</tr>
<tr>
<td>Second Life [318]</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>desktop</td>
<td>voice/text</td>
<td></td>
<td>2003</td>
</tr>
<tr>
<td>(m)CLEV-R [239]</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>desktop, mobile</td>
<td>text/voice</td>
<td></td>
<td>2005</td>
</tr>
<tr>
<td>AWEDU [61]</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>desktop</td>
<td>text</td>
<td></td>
<td>2005</td>
</tr>
<tr>
<td>SMART [113]</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>webcam AR</td>
<td>verbal</td>
<td></td>
<td>2008</td>
</tr>
<tr>
<td>Valladolid Serious Game [407]</td>
<td></td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>3DTV, Projector</td>
<td>verbal</td>
<td></td>
<td>2013</td>
</tr>
<tr>
<td>Group-to-Group Tele-presence [23]</td>
<td>x</td>
<td></td>
<td>remote/local</td>
<td>indirect</td>
<td>Single wall-CAVE</td>
<td>voice</td>
<td></td>
<td>2013</td>
<td></td>
</tr>
<tr>
<td>AltSpaceVR (“AltspaceVR,” 201Cre)</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>desktop, HMD,</td>
<td>voice</td>
<td></td>
<td>2016</td>
</tr>
<tr>
<td>Google Expeditions [126]</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>local</td>
<td>Google HMD, Mobile</td>
<td>verbal</td>
<td>2016</td>
</tr>
<tr>
<td>High Fidelity [141]</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>HMD</td>
<td>voice/text</td>
<td></td>
<td>2016</td>
</tr>
<tr>
<td>Rec Room [293]</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>desktop, HMD,</td>
<td>mobile voice</td>
<td></td>
<td>2016</td>
</tr>
<tr>
<td>VRChat [379]</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>desktop, HMD</td>
<td>voice</td>
<td></td>
<td>2017</td>
</tr>
<tr>
<td>Mozilla Hubs [246]</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td>desktop, HMD,</td>
<td>mobile voice</td>
<td></td>
<td>2018</td>
</tr>
</tbody>
</table>

1 AR mode is an entirely different experience. Not apparent that it can mix with VR experience.
2 Mobile/tablet mode is instructor only.
3 Whether direct (collaborative) or indirect (no interactions that can only be performed together – just gestures and voice to work cooperate).

It should also be noted that no social VR platform currently supports co-located experiences that allow learners to move around together within a shared physical space. Allowing learners in VR to use their bodies to move around an area is more immersive
and yet there is still no clear example of how to prevent issues such as collisions in HMD VR, though there has been some general work in exploring potential solutions [191, 312]. However, within AR, we do see many examples of co-located social learning experiences [334]. This is likely due to AR’s more accessible nature in a multi-user context (i.e., can see others sharing the space more efficiently than within VR). Where there is VR co-located learning, in the case of Google Expeditions [126], only seated VR experiences are supported, with minimal multi-user interactions, (i.e., students cannot actively move around the class and interact with each other physically); or a highly complex and low-immersion apparatus (arguably closer to the AR side of Milgram’s reality-virtuality spectrum [235]) is required, as in the case of the “Group-to-Group” telepresence with projected screens [23].

2.11 Discussion

In this section, we describe the common themes found within our overview of the literature. Also, we highlight exciting but under-researched areas of research into VR/AR technology. There appears to be minimal research on the use of both VR and AR or a comparison between the two different technologies in their effectiveness for educational applications in similar experimental setups. Research on the individual technologies is also incomplete and conflicting, but even so, there is strong motivation to not treat VR/AR as two completely separate technologies but instead as a spectrum between “virtual/physical” to “completely virtual” [235]. We also try to take the affordances discussed in Section 4.3 and separate them into Table 3 as either VR, AR, or VR/AR shared affordances with a few additions. Table 4 also highlights some examples of learning with AR and VR as both individual and social learning use-cases. Within the literature, we can point to several principles that will likely be important when considering state of the art, and the future, of VR/AR in education.

2.11.1 Consideration of Technological Limits

Chris Dede notes, in his paper on “Immersive Interfaces in for Engagement and Learning” that “understanding the strengths and limits of these immersive media for education is
important, particularly because situated learning seems a promising method for learning sophisticated cognitive skills, such as using inquiry to find and solve problems in complicated situations” [70]. It is a reminder that technology should be considered part of the design for an educational lesson as opposed to the technology being projected onto an existing traditional lesson. The limits of the interaction and display methods should also be noted so that a lesson can be created that focuses on the strengths of the technologies (e.g., embodiment and presence) and not so much on its weaknesses (e.g., resolution, lack of 6DOF in some mobile VR/AR, complex/unsatisfactory interaction methods). In this regard, it should be noted that some researchers feel that there is still potential in combining both traditional and “new technology” lessons to help bring in “new and old” learners [158].

2.11.2 Not a Replacement

Liarokapis and Anderson note that “AR technology is a promising and stimulating tool for learning and that it can be effective when used in parallel with traditional methods” [201]. This is an important note as neither AR nor VR can display virtual environments indistinguishable from physical environments at this time. VR/AR technology is merely a tool to help augment and enhance existing educational methods rather than replace them - perhaps by offering multiple unique frames of reference [302].

2.11.3 Conflicting and Ambiguous Results

Due to the lack of standardization and attempts to reproduce other research results, there is conflict within the literature as to what “the best practices” are for VR/AR in education. Merchant et al. found that VR games were most effective as learning tools and that surprisingly individual play was more effective than collaborative play [224], though this could be countered by other work suggesting individual “play” is also essential in fostering group activities [305]. Still, other researchers, such as those within the medical anatomy field, do not find any significant advantage of 3D models over physical models in knowledge retention [119, 282], though the benefits of reduced storage space, that one virtual model can serve several students simultaneously, and the remote interaction
possibilities of virtual models are significant. However, they do note it could be due to limitations within the study - perhaps HMD VR or AR with 6DOF (more immersive technologies) would create a better result? This is also noted by Du and Arya in their research into an Optical Head-mounted display (OHMD) learning assistant [80].

There is a lack of conclusive evidence that suggests that 3D VLEs support learning well [66], echoed again by Fowler that more concrete guidelines for creating VR learning content would help [110]. Additionally, Merchant et al. conclude that though VR instruction is effective, that there are caveats, such as repeated assessments reducing learning gains [224]. There is much work to be done in standardizing the shared terminology surrounding VR/AR, how we measure effectiveness, and what pedagogy designs should be based on. These types of difficulties in validating learning gains with VR/AR learning activities is well summarized by Dede and Richards whom acknowledge that designing, assessing, and creating VR/AR learning content, within various learning contexts and with various learners, is challenging but still a significant endeavour going forward [71].

2.11.4 Importance of Embodiment

As noted by several researchers, one of the main advantages of VR is the use of embodied interaction, whereby users feel as if they are strongly connected, to their avatars within a virtual environment [9, 70, 165, 270, 396]. Though embodying virtual avatars is something that is seen in VR, rather than AR, AR examples may become more common as we use virtual dressing rooms [1] to change appearance, and potentially, combine VR and AR multi-user experiences where AR avatars may become necessary for visualization by VR learners. To help users feel as if they are more immersed in virtual environments, and acting within them, we can look to some of the research done on the “Proteus Effect” or body transfer, an element of embodied cognition, which describes how users assume the perceived behavioural characteristics of their virtual avatars [329, 400], or even for learners to assume non-human characteristics [351]. This will help us understand how to keep the presence high while not necessarily striving for authenticity, or hyper-realism [162, 410], as though embodied interactions are important for learning [165] there is some
research suggesting that for increased accessibility some less-immersive interactions are also meaningful [298].

2.11.5 Accessibility

As noted previously, there are still many avenues to explore in determining the most effective techniques for utilizing VR/AR technologies in education. This includes students with special needs as they may not be able to use technologies that require subtle movements with their bodies, such as HMD VR. For example, “AccessibleLocomotionWebXR” was an explorative project, created at the 2019 MIT Media Lab “Reality Virtually” hackathon, that developed an HMD VR component that allowed users to navigate and interact with just a single input [6]. Also, within the broader context of Universal Design for Learning (UDL), how do we make sure the learning technologies and materials can adapt to learners with various needs and preferences [299]. As noted by others “in the studies reviewed from journals there was no evidence of AR applications in educational settings that address the special needs of students” [21], and that social VR can be uncomfortable for women [390], or for anyone using unfamiliar technology, such as interactive screens [41] or HMD VRs [298, 340] in social environments. Bodén et al. have the following suggestions for AR, which could be applicable to social VR also [32]:

- AR needs to be as time-efficient as existing methods of teaching.
- The exploration performed with AR needs to be guided as to maximize learning.
- AR within classroom environments needs to be designed for the institutional context.

Platforms such as WebXR [386], which support desktop, mobile, and HMD VR/AR, will help in this regard as they will force VR/AR application developers to consider multiple, accessible, forms of display and input technologies, which can help inform experiential learning methods/strategies in VR/AR.
2.11.6 Content Creation

Often, the process of content creation is a complex task left to knowledgeable developers and designers, as an afterthought, rather than being accessible to low-technical knowledge users such as instructors and learners. There are some examples of commercial software such as VRChat [379], and Second Life [318] allowing import of previously created 3D avatars and environments but this often still requires some knowledge on where to find, update, and adapt these models. For a learning platform, that one would hope to be successful, there should be considerations on how to allow low technical knowledge end-users to create, or piece together, their content as environments, interactions, and learning experiences. It could take the form of a marketplace as found in Second Life; perhaps as an online repository of virtual experiences such as might be found in endeavours to make all of the web-accessible in WebXR [356] or Mozilla’s “Spoke” [247] for creating and importing content into Mozilla Hubs [246]. These types of content creation or “content collage” tools for VR/AR content in learning are preceded by the structure of most LMSs that allow instructors to bring together modules to create custom online learning environments.

2.11.7 VR versus AR

There are few examples, both within educational contexts and otherwise, that support both VR and AR. VR and AR share many similarities, and researchers such as Milgram et al. group them into a spectrum [235] with Mozilla Mixed Reality Research recently publishing blog posts on designing for both simultaneously in WebXR [284]. It seems inevitable that VR/AR platforms of the future will incorporate both VR and AR modes. This could merely be the detection of the environment and people around us to prevent collisions [312], incorporating humans’ limbs into VR environments via the depth-sensing technologies such as the Leap Motion [197], Kinect [73], and the Logitech “Bridge” VR keyboard [155] (arguably an example of AV, Augmented Virtuality [235]). Also, perhaps, it could be something more intrinsically tied to the type of educational experience we are striving for, taking into consideration both individual and social accessibility along with subject matter.
2.11.8 Challenges of Implementing VR/AR in the classroom

There are several challenges to implementing VR/AR into formal educational curriculums in classrooms. Some of these relate to teacher training and student expectations, where systems such as Google Expeditions [126] requires some, albeit minimal, setup and instruction on how teachers and students can navigate the system. In several studies, technology pitfalls provide for some muddled empirical results, creating “false expectations” [32] of interactions. This concept was noted in varying forms within the literature - that interactions were not always clear and that the affordances of digital technology somewhat limits the freedom of movement and interactions within the virtual world. Additionally, the cost of VR/AR equipment may still be an issue – listed as the second primary concern after user experience by Perkins Coie [412], and so a platform and framework that includes lower-cost entry points such as allowing personal smartphones to access content (e.g., Google Cardboard or WebXR) will be important. Currently, much of the research cited in this survey focus on post-secondary education and, in most cases, we can assume most students have access to a smartphone.

How the technology is used is also essential, and researcher Ed Smeets notes “93% of teachers surveyed had implemented some form of technology integration into learning, but rather that the technology is being used for skill-based learning, as opposed to supporting deeper levels of learning” [331]. Bodén et al. suggest “teachers should be educated on methods in which they can adapt existing technologies to support their learning structures purposefully, rather than treating technologies such as computers as isolated activities” [32]. There is more research required to find stronger correlations between the use of VR/AR in learning and more traditional educational media.

Dalgarno et al. note in their paper on learning affordances in virtual worlds “currently, design and development efforts in this field are largely hit-and-miss, driven by intuition and ‘common-sense’ extrapolations rather than being solidly underpinned by research-informed models and frameworks” [66]. Some results also appear to conflict, as within the literature where anatomy research suggests that 3D virtual models are not much better than physical models [119, 282]; or that many researchers have focused on the social
learning aspect of their systems; but that still other researchers find “game-based learning environments were more effective than virtual worlds or simulations” [224].

The technology also remains a barrier for implementing VR/AR into classrooms easily as there are many resources required to build content (3D modeling, texturing for building VEs, developing systems capable of displaying 3D content, and handling many simultaneous connections, etc.). Utilizing more accessible technologies such as WebXR [386] and A-Frame [7] could be helpful in this regard – allowing for a large community of resources and accessible technologies to create content. Unfortunately, there are few examples of this type of technology for educational content delivery with “low-friction” interactions [308]. There are a few pre-made systems for use within educational institutions, but thus far, no widespread adoption and system stands out to minimize financial risk to institutions. From the user’s perspective, there is also still much work to be done on standardizing interactions and allowing explorations of the virtual worlds without users feeling too constrained by the system. Current input methods for interacting with the world with the HTC Vive, Oculus Rift, and Google Cardboard lack true haptic (physical) feedback, for example; and currently do not have any method for preventing collisions between multiple users sharing the same physical space [191, 312].

Another concern is in the widespread adoption of VR/AR as educational tools are in their accessibility. Current popular methods of VR involve stereoscopic HMDs that may not work as well for those that have vision problems, and mobility issues could make using AR platforms or VR/AR inputs/controllers difficult. These accessibility concerns may also apply to the social embarrassment or social anxiety of using VR/AR around others [298, 340] until the technology is more widely adopted. Though touched on briefly by some papers cited within this survey, more work needs to be done in allowing these systems to better degrade into experiences/platforms that can be used by students with a wide range of varied accessibility issues within modern implementations of VR/AR technology.
Table 4. Table describing the basic affordances of VR/AR, building from prior research while also highlighting differences between VR and AR.

**Affordances of VR/AR Forms**

<table>
<thead>
<tr>
<th>VR</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>• High presence (HMD)</td>
<td>• Body Awareness &amp; Skills</td>
</tr>
<tr>
<td>• Not constrained by physical reality</td>
<td>• Environment Awareness &amp; Skills</td>
</tr>
<tr>
<td>• Allows for private experiences</td>
<td>• Social Awareness &amp; Skills</td>
</tr>
<tr>
<td>• Increased Embodiment (Proteus Effect)</td>
<td>• Context-aware (i.e. physical location)</td>
</tr>
<tr>
<td>• Multiple frames of reference</td>
<td>• The range of social collaboration.</td>
</tr>
<tr>
<td>• Reduced possibility of cybersickness</td>
<td>• Reduced possibility of cybersickness</td>
</tr>
<tr>
<td>(non-HMD)</td>
<td></td>
</tr>
</tbody>
</table>

**Shared Affordances**

- Enhanced spatial knowledge
- Greater opportunities for experiential learning
- Increased motivation / engagement
- Possibilities for situated/contextualized Learning (near-transfer)
- Richer/more effective social learning
- Multisensory Cues

Table 5. Some examples of solo/multi-user experiences within either a VR or AR context.

<table>
<thead>
<tr>
<th>Solo</th>
<th>Multi-user</th>
</tr>
</thead>
<tbody>
<tr>
<td>VR</td>
<td></td>
</tr>
<tr>
<td>• At-home study of a VE before a class discussion.</td>
<td>• Constructing large artefacts (e.g. a building or gazebo)</td>
</tr>
<tr>
<td>• Experiencing a historical recreation, with the VR platform minimizing distraction.</td>
<td>• Solving collaborative puzzles together within VEs (e.g. virtual escape room).</td>
</tr>
<tr>
<td>AR</td>
<td></td>
</tr>
<tr>
<td>• Study of physical artefacts or environments with virtual extra information overlaid.</td>
<td>• Location-based inquiry (e.g. exploring a physical environment augmented with historical Points of Interest)</td>
</tr>
<tr>
<td>• Study of virtual artefacts overlaid within physical environments.</td>
<td>• Encouragement of indirect collaborative methods with voice and gestures.</td>
</tr>
</tbody>
</table>

2.11.9 *Future Research Directions for VR/AR in Education*

As noted in the previous sections, there are many exciting facets to consider when looking to create VR/AR applications in social learning spaces. Generally, three primary areas of interest and research direction that become uniquely apparent are accessibility, the unclear interplay between parallel realities (the virtual and the physical) in learning, and the learning theories and methodologies that can better support VR/AR learning within social learning spaces. Additionally, we must also always look to observing and verifying,
through experimental rigor, how VR/AR can help enhance educational practices, propagating the use of these specific tools within these learning contexts [66, 110]. Researchers note there are not enough real-world case studies on the use of VR/AR for learning, particularly HMD VR [216], and that researchers struggle to find will to engage with the risk-taking required to try out these technologies within authentic contexts [71].

2.11.10 Accessibility

As discussed in the previous section, accessibility will always be a significant concern for any learning materials as learning is not exclusive to one group of people; but rather to all. When we consider social learning spaces, such as classrooms and museums, we must also consider how to make sure that the technology we use within these spaces enhances learning rather than hindering it. We suggest three specific areas that where further exploration can help make the use of VR/AR in the classrooms better follow UDL principles in creating content and technology adaptable to a variety of learners – as individuals and as groups of individuals learning together.

2.11.11 Platform Scalability

Refers to creating a framework that adapts to a range of VR/AR capable platforms (desktop, mobile, large screens, etc.). This is comparable to a virtual form of Universal Design for Learning (UDL), which describes how to increase the accessibility of learning materials via (1) Multiple Means of Representation, (2) Multiple Means of Expression, and (3) Multiple Means of Engagement [299]. By supporting multiple platforms, VR/AR content can be potentially more accessible with “multiple means of expression.” WebXR, as a possible solution, supports many of these platforms; but more research into this area would help understand and design how interactions, navigation, and embodiment in an education context may change as one moves between platforms. This is especially important in social learning spaces as prior research into public technology use suggests that “social embarrassment” may limit the use of unfamiliar devices [41], including papers that suggest that “the awkwardness of physically moving in VR with an onlooker”
may also be an issue in VR [298], and that female students may be more hesitant to wear HMD VR in social spaces [340].

The effect of the social environment when using technology falls well in line with recent work that suggests that social facilitation (simple tasks easier with an onlooker) and social inhibition (complex tasks more difficult with an onlooker) also applies to completely virtual avatars [236], and that learning theories such as social cognitive theory and activity theory will be critical in helping to define the social relationships between technology and learners. Additionally, cybersickness in HMD VR is still an active line of research due to its effect remaining present in the population, even with access contemporary VR systems [136, 210]; and even though its effects can be minimized by features such as reducing fast motions into discrete rotation and translation “viewpoint snapping” [98], the ability to choose another platform, such as desktop or mobile, that suffers less from these problems is worthwhile.

- Does responsive VR/AR design that adapts the platform accessing content, increase engagement, and participation in learning?

- What are the best practices for adapting interaction types across multiple platforms?

- Does social embarrassment/social anxiety limit the use of some VR/AR platforms (e.g., HMDs), limiting learning?

2.11.12 Social Scalability

This concept is based on Snibbe et al.’s definition of social scalability within a museum context: “Interactions are designed to share with others … interaction, representation, and users’ engagement and satisfaction should become richer as more people interact” [334]. This definition could expand to include VR/AR multi-user applications that support variable numbers of remote (to reduce geographical barriers) and co-located (classroom) users working together towards shared goals. This would build from Roberts et al.’s explorations into supporting teamwork via tightly coupled interactions [268, 295] but
could also include discussions on how, or if, to support multiple co-located learners in HMD VR-based platforms to prevent collisions between learners and objects.

- How does social scalability affect co-presence and learning outcomes?
- What do socially scalable interactions look like in VR/AR learning?
- How do remote and local learners communicate and interact together in virtual spaces?

2.11.13 Reality Scalability

This refers to the concept of an application allowing both VR and AR perspectives. Some studies explore “mixed-space collaboration” [129] and VR and AR collaborative interfaces [131] but there are few examples of explorations of these techniques within education; particularly when considering not just remote collaboration but also co-located collaboration between peers. As noted within the prior section on platform scalability, allowing learners to use a platform such as AR, over VR, may be preferred as they can be more aware of the social environment.

- Are there any learning advantages for adopting non-egocentric viewpoints?
- How do we design a Virtual Learning Environment (VLE) for switching between VR and AR?
- How do we synchronize users, environments, and real/virtual objects between physical and virtual locations in AR and VR?

2.11.14 Parallel Realities

There is some work looking at how the virtual work can affect our reality, in how we identify in virtual worlds can change our behaviour [400], in how task performance can be affected by others through social facilitation and social inhibition [236], and in how virtual spaces can also change behaviour [207, 285]; but there is still much work to be done on how the physical learning spaces we inhabit may affect our virtual behaviours.
We have seen that the very nature of using this technology can inhibit participation and comfort [41, 298, 390]; but it is emerging work beyond some studies into how we prevent collisions in shared virtual spaces [191, 312]. Just as connectivism and activity theory espouses that our digital tools and the socio-historical culture that surround learners become intrinsic part of the learning process, we should also consider how these same processes apply to both virtual environments and physical worlds as it becomes clear that the virtual worlds and physical worlds are not mutually exclusive entities but tied together into parallel realities that affect each other and every individual within them in strange and exciting ways [352]. Notably, as we consider how increasingly blurred the lines between VR and AR become in modern HMDs that support both via hand-tracking, windows into the physical world, and potentially, in the future, virtual spaces that scan and enhance our physical spaces digitally [343].

- How does the interplay between the virtual and physical spaces help or hinder learning?
- What are the ethics that surround the use of VR/AR that enhances or augments reality with measurable behavioural effects?
- Does the interplay of the physical and virtual realities necessitate the construction of physical learning spaces built with virtual world modelling in mind?

2.11.15 Learning Foundations

Though most VR/AR projects in learning depend on constructivism, experiential learning, and/or social cognitive theory as a foundation for chosen features and properties, there are additional theoretical and methodological foundations within CSCL that may help lend more significant consideration to both the virtual and physical environments within a socio-cultural context. Activity theory, in the form of expansive learning, includes not only digital tools and objects/artefacts as an intrinsic part of the learning process; but also the socio-historical properties of learning spaces [88, 346]. This could include some exciting explorations into the interplay between the social, spatial, and
cultural aspects present within both the virtual and physical learning spaces; and how to better create VR/AR content that acknowledges them, such as how wearing in HMDs in learning spaces is not yet culturally acceptable [298], or that being a women in social VR spaces may encourage virtual harassment and decrease participation in activities using these technologies [390]. The interconnected processes of learning within individuals and their actions, the social environment, and the spatial environments are complex, and as we add in virtual environments that may change behaviour, we may need to look towards additional learning theories that better encapsulate how this learning happens. In the case of activity theory there is already precedent for exploring its use in HCI [186], with some reality-based interaction frameworks echoing similar principles about greater consideration of social skills and environment [159, 334], and in learning [88], and thus appears a good candidate for future explorations including VR/AR.

- What is the effect of the socio-cultural context on VR/AR learning performance?
- Are learning theories from other fields, such as activity theory, worth exploring for use within VR/AR in social learning spaces?
- How do existing learning theories apply to two parallel realities (physical and virtual)?

2.11.16 Summary
The future of VR/AR in education will involve the use of a platform, not unlike current LMS/CMS systems used within educational institutions such as schools and museums, built with more significant consideration of accessibility and the interplay between the virtual and physical, social and individual, in mind. Note that a VR/AR platform need not be mutually exclusive from current LMSs and could extend their existing functionality. These frameworks and platforms will allow instructors and directors to not only customize content but also help direct it live while learners explore it with VR and/or AR platforms. Desktop VR/AR systems will likely cede to, or work with, smaller mobile implementations such as the Google Expeditions system [126] and standalone platforms.
such as the Oculus Quest and/or Microsoft Hololens with high-quality input and output controls that will allow for more natural interactions within the world. This is perhaps where existing research into Reality-Based Interactions using full-body and gestural inputs can be useful [159, 334] as it allows another perspective into how we can have multiple learners interacting together in a genuinely collaborative manner [132, 169, 310].

2.12 Conclusion

In this survey, we explored the use of VR and AR for education within social learning spaces, while also highlighting many areas of research and development to explore. We suggest that VR/AR educational platforms should include accessibility as a primary concern across three main areas: Platform scalability, Social Scalability, and Reality Scalability for better UDL considerations [299] and more accessible social engagement between learners sharing the same physical learning space. We also suggest that greater consideration should be placed on exploring the interplay with virtual and physical realities, and on additional learning theories that may better guide VR/AR learning within social learning spaces. With a stronger theoretical foundation and these new research directions, there are many exciting areas of VR/AR education research to explore.

Many researchers are optimistic about the use of VR/AR in education as Merchant et al. note that research into using these technologies for learning is encouraging in that they provide evidence that virtual reality-based instruction is an effective means of enhancing learning outcomes. Educational institutions planning to invest time and financial resources are likely to see the learning benefits in their students” [224]. The greatest challenge will lie in determining how best to utilize this technology to better enhance students’ learning in a manner that is not merely recreating, or replacing, the physical classroom but also enables activities, and access to facilities, that are not possible in physical settings” [17].

References

[Aggregated at the end of this thesis]
"... artistic practice can no longer revolve around the construction of objects to be consumed by a passive bystander. Instead, there must be an art of action, interfacing with reality, taking steps – however small – to repair the social bond."

Claire Bishop,
Artificial Hells: Participatory Art and the Politics of Spectatorship (2012).
Chapter 3: Circles: A VR Framework for Social Learning Spaces

This chapter’s early work has been published (or submitted) as a journal (or conference) paper:


A fully updated version is currently under peer review.


3.1 Introduction

Several organizations have proposed core competencies learners require to succeed in 21st-century classrooms, workplaces, and lifelong learning [105], such as critical thinking, communication, and collaboration [237, 413]. Bringing these competencies into post-secondary education (PSE) primarily focuses on experiential learning, which involves learning skills within environments closely matching the settings these skills will be used [2, 180]. Within social learning spaces, such as PSE classrooms and museums, where we learn together across physical and digital mediums [258, 309], the social aspect of education [88, 164, 346] is vital as we learn and work together, requiring communication and collaboration over increasingly diversified groups [230].

Unfortunately, real-world learning environments can be impractical (e.g., costly field trips) or impossible (e.g., visiting the surface of Venus). However, researchers note experiential learning to be well facilitated by VR [66, 70, 309, 322], as it promotes active participation, problem-solving, and critical thinking, allowing learners to apply knowledge in simulated real-world or imaginary scenarios. Additionally, studies into using VR to enhance perspective-taking, whereby individuals learn to better empathize with others [65, 205], suggest the VR medium is a good candidate for transformative learning, whereby learners use critical thinking to support introducing a new way of thinking and knowing [115, 228, 335].
Contemporary VR education often focus on highly immersive head-mounted displays (HMD). Yet, HMD-based VR suffers from various limitations preventing effective use in social learning spaces [46, 309, 341], such as cybersickness [292], infrastructure and training constraints [342], and various ability and gender biases [101, 245, 248]. HMD VR users may also experience social anxiety when using unfamiliar technology around others [41, 101, 298]. A VR framework that provides reasonably similar experiences across multiple platforms (HMD, desktop, and mobile) could significantly increase the inclusion and efficacy of VR in social learning spaces. Such frameworks consist of software modules, assets, documentation, and application programming interfaces (APIs) that provide easy development of new virtual environments. Currently, WebXR [386] is the only VR API supporting multiple VR platforms using standard web technologies, which provides a good foundation for developing an inclusive VR framework. Still, the user experience of WebXR-based VR has not been extensively evaluated [297, 307], with only a few studies on the WebXR-based Mozilla Hubs for conferences [196] and classrooms [90, 116, 403]. These studies note the potential of connecting with others remotely via VR and several technical and usability challenges presented by current VR frameworks.

To support inclusive VR learning activities, social, spatial, and physical accessibility concerns are particularly relevant for VR social learning spaces [121, 298, 309]. For guidance, we can look towards increasing the inclusion of VR learning activities, i.e., ensuring the active involvement of everyone to the greatest extent possible [5, 121], by combining the physical accessibility guidelines of Universal Design for Learning [222, 365] and Universal Design [365] with more social and spatial accessibility design principles found in prior reality-based and immersive interactive media [159, 309, 334]. Additionally, VR in learning environments does not integrate socio-cultural learning theories and practices beyond implied constructivism, whereby we construct meaning from our experiences [110, 309]. Thus when designing and building a social VR learning framework, we should also consider the interconnectedness of people sharing the social learning space, artefacts, environments, and tools that enhance learning [88, 185].
Creating social VR experiences and frameworks is challenging [212, 223], as noted by several recently discontinued social VR platforms such as AltSpaceVR [11, 94, 141]. Many VR frameworks are not learning-focused [246, 379]. And when the frameworks are learning-focused [111], they attempt to recreate physical classrooms and conference spaces with presentation features, moving away from the powerful experiential learning VR affordances while not fully acknowledging the socio-cultural context of learning within social learning spaces [110, 185]. Though many VR frameworks now support desktop platforms for greater accessibility, there are many usability and technical challenges in supporting multiple VR platforms [90, 403], where HMD VR can be uncomfortable when used for extended periods [162], and it may not always be better for learning [344, 403]. VR learning should focus on pedagogical foundations that best represent the reality of contemporary social learning spaces to centre on the interconnectedness of learning artefacts, tools, individuals, communities, and deeper understanding [88, 185, 309]. As such, we are interested in exploring an alternative form of VR use in learning that extends social learning spaces rather than attempting to replace them.

Our discussed VR learning framework, Circles, aims to provide a simple entry point for other developers to create VR learning activities focusing on critical thinking, collaboration, and communication around virtual learning environments (VLEs) and virtual learning artefacts (VLAs). We chose WebXR as the foundational API for Circles to support multiple VR platforms (desktop, mobile, and HMD) [307, 386] and to use standard web-based technologies that PSE institutions already use for their web-based learning-management systems (LMSs) [221]. Circles is highly extensible using the modular entity-component system (ECS) programming design pattern provided by the generalist WebXR library A-Frame [7] and supports existing A-frame developer content and Circles-specific components. Using an ECS to add and remove functionality on entities follows a familiar process to existing web applications and the popular Unity gaming engine [373]. Additionally, an ECS helps prevents Circles from becoming a “big ball of mud” [109], i.e., a haphazardly structured system. In this paper, we describe the design and development of a VR learning framework called Circles that aims to provide more engaging, inclusive, experiential, and community learning experiences within social
learning spaces. We also describe some of the VLEs and VLAs built using Circles, as they guided feature requirements while keeping the feature set streamlined to avoid overwhelming new users and developers. These brief case studies also help us move forward to evaluate our design decisions through Circles’ iterative development and provide examples of the type of work Circles supports. We should also note that this paper focuses primarily on the design and implementation decisions from a developer's point-of-view rather than the end users, e.g., learners and instructors, which researchers have studied previously [307]. As we built Circles from existing frameworks, such as A-Frame, our contribution focuses on the unique core concepts, elements, and features described in our design overview rather than a specific coding pattern or style [108]. Our research questions around building Circles follow:

1. How can we build a VR framework to increase engagement and inclusion within VR learning activities?

2. How to make it easier to create VLEs and VLAs that encourage communication, collaboration, and critical thinking within a transformative learning context?

3. How do alternative learning methodologies considering a socio-cultural pedagogy change the foundation for VR design decisions within social learning spaces?

After several years of development and study, our primary contribution is to explore the above questions by disseminating the design, development, observations, and evaluation of Circles from an alternative perspective that considers VR in learning as an extension of social learning spaces, where learners' journey through both virtual and physical realities to transform their understanding of the universe around them.

3.2 Design Overview

Circles provides an inclusive and engaging VR framework developed from a socio-cultural perspective to explore an alternative direction to a VR learning framework based on inclusion, communication, collaboration, and critical thinking skills. This section
overviews the core concepts, elements, features, interactions, technology, and system architecture.

3.2.1 Core Concepts

We built Circles on top of the existing WebXR libraries A-Frame [7] and Networked-Aframe [254], inspired by Mozilla Hubs [246]. These platforms showcase practices we emulate to retain familiarity with programming design patterns to support developers familiar with A-Frame and allow using existing A-Frame libraries and components. Circles differentiates itself by connecting A-Frame, Networked-Aframe, a database, and a node.js server to provide additional networked and non-networked components and multi-world elements for more collaborative and transformative experiences. Circles’ social offerings focus on continuously connecting others in the same learning group, even when in different VLEs. The Circles’ VLEs and VLAs also encourage critical thinking, reflection, and inquiry-based learning within a socio-cultural context. Additionally, Circles focuses on creating a more inclusive foundation with predominantly symmetric single-selection interactions to provide a similar method of low-effort interactions across all supported VR platforms (desktop, mobile, HMD).

3.2.2 Assumptions

In designing a VR learning framework, we make several assumptions about the users, social learning spaces, and technology associated with Circles. Our assumptions include the following:
• Target users are:
  
  o **Learners** will explore and interact with others within the VLEs.
  
  o **Instructors** will manage group and circle creation for learners, and guide them through experiences, if a guided learning activity. Note that instructors may also take on a developer role.
  
  o **Developers** create new worlds using the Circles framework. Developers can also include designers, e.g., 3D and sound artists.
  
• The framework should support desktop, mobile, and HMD platforms with feature parity and equivalent interactions.
  
• This framework will not rely on past user experience with VR and will focus on smaller group sizes (less than 15 users).
  
• Web-based technologies, e.g., HTML and Javascript, are more accessible to developers already using web-based learning management systems.
  
• Content creation, especially 3D modelling, is a significant bottleneck in VR development, but our current focus is on development.

**3.2.3 Primary Objectives**

The three primary objectives (*engagement and inclusion, exploring alternate learning foundations, and exploring an alternate VR learning framework*) of Circles follow, inducted from previous work [308, 309].

**Engagement and Inclusion**

Though increased engagement is a commonly noted affordance of VR use in learning, increased inclusion is less so. While developing Circles, we built a framework that considers engagement and inclusion as core concepts for VR-based learning. We turned to several existing frameworks to enhance inclusion in digital spaces. Universal design
for learning (UDL) suggests multiple means of engagement, representation, and expression [299]. Universal design (UD) [365] provides several interface and interaction development principles. Additionally, we can look towards more reality-based interactions (RBI) [159] and social immersive media (SIM) [334] design principles to consider how to connect immersive digital content with our bodies, environments, and others around us. Circles’ five guiding principles of inclusion and engagement are described in Table 6, and extend principles suggested in previous papers [309].

Table 6. Circles’ five guiding principles are inspired by UDL, UD, RBI, and SIM design principles (described within). These align with Circles’ features described in Section 2.3.

<table>
<thead>
<tr>
<th>Guiding Principle</th>
<th>Description</th>
<th>Design Principle(s) Covered</th>
<th>Circles Feature(s)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Platform</strong></td>
<td>Supporting multiple VR platforms (desktop, mobile, and HMD).</td>
<td>• UDL-“multiple means of representation”</td>
<td>supporting desktop, HMD, mobile display and interactions</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>• UD-“flexibility in use”</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• RBI-“body awareness and skills”</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Social</strong></td>
<td>Supporting a variable number of users together and alone, encouraging multi-user interactions.</td>
<td>• RBI-“social awareness and skills.”</td>
<td>avatar visualization, voice communication, costumes, the networking layer</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>• SIM-”socially scalable”</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• SIM-“socially flexible”</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Reality</strong></td>
<td>Encouraging the design process to consider physical and virtual realities and their interconnectivity.</td>
<td>• UD-“low physical effort”</td>
<td>checkpoint locomotion, multi-platform for social anxiety</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>• UD-“size and space for approach and use”</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• RBI-“environment awareness and skills”</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Interaction</strong></td>
<td>Interactions are low physical effort selection-focused scaling to advanced controls for experienced VR users.</td>
<td>• UD-“low physical effort”</td>
<td>symmetric selection interactions, advanced immersive interactions</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>• UD-“simple and intuitive use”</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• SIM-“visceral”</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Information</strong></td>
<td>Encouraging the use of multiple sensory modalities and consideration of how we communicate information to others.</td>
<td>• UDL-“multiple means of expression”</td>
<td>circles’ components for artefacts, text, sound, UI, and 3D models</td>
</tr>
<tr>
<td><strong>Scalability</strong></td>
<td>• UD-“perceptible information”</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• SIM-“visceral”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Exploring Alternative Learning Foundations**

Though most VR educational platforms support constructivism and experiential learning as a foundation, it is not always clear how developers connect these decisions to chosen feature sets [71, 110]. Additionally, other theoretical and methodological foundations
within Computer-Supported Collaborative Learning (CSCL) [346] may provide a better context for virtual and physical environments in socio-cultural contexts. Activity theory includes not only tools, which can be digital, and artefacts as an interconnected part of the learning process but also the socio-cultural properties of learning spaces, individuals, learning outcomes, and communities involved in their construction [88, 185, 346]. Furthermore, Circles focuses on transforming individuals to process and reflect on relationships to the learning material that asks us to critically evaluate held assumptions, beliefs, values, and perspectives to create new perspectives [64, 205, 228]. Activity theory and transformative learning pedagogical foundations provide a solid roadmap for designing a VR framework to acknowledge the potential of how we learn within social learning spaces [309].

Figure 3. Highlighting the relationships between an individual (avatar in the VR space), a group (a collection of avatars that can see and interact with each other), and a circle (a group of avatars visiting one or more Circles’ worlds/VLEs).

Exploring An Alternate VR Learning Framework

Many social VR platforms focus on social, professional, and learning contexts, but some creators have discontinued their platforms [95, 142, 232], highlighting the challenges in connecting people through VR [212]. Additionally, it is unclear why developers made the underlying design decisions and added features for many of these social VR experiences
When looking at learning-specific frameworks, the pedagogy is not explicit [110], and it appears most of these frameworks focus on presentation and communication features [111, 246]. By building a new approach to VR learning framework design and development, we can more methodically document our design process and question underlying assumptions about using VR within social learning spaces from a socio-cultural pedagogy [88, 185].

### 3.3 Core Elements

The following describes the core elements of the Circles platform that focus on inclusion, communication, collaboration, and critical thinking learning skills.

- **Circle**: A circle is a collection of learners and VLEs. A “circle” allows a group or "room" of learners to visit each VLE synchronously while maintaining visual contact and communication with others (even if within different VLEs - Figure 3). E.g., interactions in a circle could involve sharing an artefact from one VLE with another learner in another VLE (Figure 4).

- **Artefact**: Our framework has been developed with social narrative in mind, as storytelling is a powerful teaching tool [64, 112, 145, 300]. There are several VLAs displayed in a world that learners can pick up, manipulate, read, and listen to learn more about its relationship to the VLE in which it exists (Figure 4, “math homework”).

- **World**: A world can be any VLE created to share knowledge about a specific person, event, or place (Section 4 describes worlds created in Circles).

- **Axis**: A unique world that connects other worlds to provide a VLE for group processing and reflection, e.g., the campfire (Figure 2).

- **Group**: An exclusive collection of users (invited to a circle by an instructor) that can explore worlds together (Figure 3).
3.4 Core Features

There are standard features within existing VR frameworks, such as Mozilla Hubs or AltSpaceVR. These include object interactions, virtual environments, avatar visualization, and some form of communication, e.g., voice communication [309]. However, there is room for exploring alternative VR learning frameworks based on alternative socio-cultural and transformative pedagogy. By referencing the primary objectives described in Section 2.1.3, and the resulting guiding principles from Table 6, we highlight several core features that extend from previous efforts focusing primarily on the presentation and communication spaces to expand into more engaging, inclusive, and transformative learning experiences.

Table 7. Circles has several core features based on the guiding principles described in Table 6.

<table>
<thead>
<tr>
<th>Features</th>
<th>Description</th>
<th>Scalability Principle(s) Covered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-Platform</td>
<td>Experiences work across three VR platforms (desktop, mobile, HMD)</td>
<td>Platform Scalability</td>
</tr>
<tr>
<td><strong>Symmetric Selection Interactions (SSI)</strong></td>
<td>Object and locomotion interactions require only a single selection to use. E.g., select an artefact to pick up, drop, manipulate and click to teleport. SSI helps users understand the interaction when switching between VR platforms. SSI also allows minimal physical movement, avoiding conflict with their physical environment.</td>
<td>Platform Scalability, Interaction, Scalability, Reality, Scalability</td>
</tr>
<tr>
<td><strong>Advanced Interactions</strong></td>
<td>Some more advanced users wish for more complex controls to be more immersed. E.g., smooth locomotion is triggered with an HMD controller joystick or desktop WASD keys.</td>
<td>Interaction, Scalability</td>
</tr>
<tr>
<td><strong>Circles Artefact</strong></td>
<td>Knowledge transfer focuses on virtual learning artefacts that are manipulated to access textual, audio, and visual information about the learning subject.</td>
<td>Information, Scalability</td>
</tr>
<tr>
<td><strong>Multi-world</strong></td>
<td>Circles encourages the creation of multiple worlds to explore different themes within the same subject area, including axis worlds, to connect them all via circles-portals.</td>
<td>Information, Scalability, Social Scalability</td>
</tr>
<tr>
<td><strong>Axis Worlds</strong></td>
<td>Circles encourages a &quot;connecting&quot; world that allows other worlds to be connected to it (via hyperlink portals). These axis worlds, e.g., a campfire in Figure 1, will give learners a natural social reflection and discussion area.</td>
<td>Social Scalability</td>
</tr>
<tr>
<td><strong>Multi-World Avatar and Artefact Visualization</strong></td>
<td>Learners can see each other as avatars within Circles' worlds/VLEs, even if not currently in the same VLE. They can even pass artefacts found in one world to another learner in another world (Figure 3).</td>
<td>Social Scalability</td>
</tr>
<tr>
<td><strong>Networked Interactions</strong></td>
<td>Circles’ includes a system to make networked objects, interactions, and messages within Circles' worlds. E.g., sharing artefacts between each other, having system-wide events happen like a campfire turning off/on for everyone, and connecting interactive and non-interactive objects across clients for more collaborative interactions.</td>
<td>Social Scalability</td>
</tr>
<tr>
<td><strong>Roles</strong></td>
<td>Several roles within Circles, e.g., student, teacher, researcher, and participant, allow certain users different abilities or permissions. E.g., only a researcher can collect data, and a teacher can create &quot;magic links&quot; to anonymize others to their group.</td>
<td>Social Scalability</td>
</tr>
</tbody>
</table>
3.5 Interactions

Circles supports the actions of object interaction, viewpoint control, and locomotion across desktop, mobile, and HMD VR platforms. Using symmetric selection-based techniques for object selection and travel allows us to keep them similar across all VR platforms (Figure 5). Where they cannot be identical, we defer to the default equivalent behaviours in the A-frame library, e.g., viewpoint control handled by device orientation on mobile and HMD. We also note collaborative interactions built into Circles. We describe these individual and social interactions in this section.

![Figure 5](image)

Figure 5. From left to right, symmetric single-selection interactions are showcased on desktop (mouse click), mobile (finger-tap), and HMD (controller trigger-click on ray cast selection).

3.5.1 Object Interactions

Circles uses symmetric selections for object interactions, pick-up, release, manipulation, and locomotion via checkpoints and portals (Figure 6), i.e., there is similar functionality across all VR platforms. Although various VR platforms have various interaction possibilities (e.g., HMD hand tracking), selection is a simple way to interact and yield a consistent experience across different hardware [99, 103, 308, 353]. These symmetric interactions may also be more understandable when switching between VR platforms for different tasks [403]. Additionally, selection is critical in social learning spaces where users may not have the physical space or abilities to use more immersive interactions, such as physically walking for locomotion or using their hands to grasp a virtual object [104, 121, 243, 306, 370]. Desktop VR uses mouse-click selection, mobile uses finger-tap selection, and HMD uses a single ray projected from the avatar's hand. Note that we are exploring how to make more advanced and immersive object interactions available to
more experienced VR learners, e.g., hand tracking with HMDs. However, the focus is currently on a “lowest common denominator” action before including other functionality.

3.5.2 Viewpoint Control

Viewpoint control is the “task of manipulating one’s perspective” [162], i.e., the user can control what is seen in a virtual environment. For these actions, we used the default A-Frame behaviours of mouse-drag for desktop and device orientation for mobile and HMD, as they are intuitive and standard interactions. We have also added smooth locomotion and “snap-turning” [100] for more advanced VR users (see the following Section 2.4.3 for more detail). However, in the future, we are also interested in exploring selection-based viewpoint control for learners with more significant physical challenges [6], as well as exploring varying options for mobile users that may find holding a mobile device up for long to be tiring - the “gorilla arm” effect [143, 162].
3.5.3 Locomotion

Following the selection design philosophy detailed above, travel in Circles also employs selection. As we generally assume that users within social learning spaces will not have much physical space, users can select bright green circles on the floor for "target-based travel" [194], i.e., they teleport to a selected “checkpoint.” Brightly coloured checkpoints also help users with wayfinding, as “local landmarks” [162] that help users visualize where they can travel through the VLEs. Although this teleportation is the primary travel technique, the desktop and HMD additionally support “smooth locomotion” using the WASD keys on desktop and the controller joysticks on the HMD to continuously move through a space. These smooth locomotion techniques directly move the user’s viewpoint in the indicated direction and are generally more challenging for new users. Notably, such locomotion in HMD-based VR is associated with the increased onset of cybersickness [98, 195], but users with previous VR experience may prefer it.

3.5.4 Collaboration

We argue that supporting collaboration is crucial in social learning spaces, and adding tools to support collaboration will enhance learning. Activity theory and other socially situated learning theories posit that learning is affected by the socio-cultural environments in which we learn. We included the following collaboration features, focusing on supporting critical thinking via transformative learning activities.

- **Group Reflection**: We created the campfire axis world to provide a universal communication space to reflect and process what learning has happened in other worlds (Figure 2). Note that other axis worlds exist to connect multiple related Circles’ worlds, e.g., the kinematics worlds in Section 4 also have an axis world.

- **Artefact Sharing**: Learners can select and pick up an object and show it to learners in other worlds, who can also see, select, and manipulate the artefact to foster discussion, collaboration, and reflection among learners.
• **Role Play**: By selecting various costume objects (bottom-right, Figure 6) within selected Circles' worlds, learners can better embody certain situations or roles within the Circles' educational narrative.

• **Voice Chat**: Circles supports voice chat among users to facilitate direct communication.

### 3.6 Technology

We specifically used the A-Frame [7] WebXR [386] library for client-side development and Networked A-Frame [254] for client-server communication (WebSockets and WebRTC [384]) to allow for multi-user networking and communication. All account information (for avatar customizations and personal preferences) is stored in a Mongo [241] database. Due to accessibility concerns (i.e., cost, setup, and wires within public spaces), Circles exclusively targets the following platforms using Chrome-based browsers for maximum WebXR compatibility and performance:

- Standalone (no requirement of a PC) VR HMD (e.g., the Meta Quest 1 [263] and Oculus browser [120])
- Mobile device (e.g., the Samsung Galaxy Tab S6 Lite tablet [117])
- PC (e.g., Google Chromebook (Google, 2023)).

### 3.7 System Architecture

Circles follows a standard web application workflow where a Node.js [257] JavaScript server connects to a Mongo [241] Javascript database and all Circles’ clients via Socket.io [337] WebSocket messages. Clients also may communicate using WebRTC, a peer-to-peer (P2P) web networking API [384], or WebSockets, a bidirectional client-server networking API [384], via the Networked-Aframe library [254]. Circles also uses WebSockets to pass messages and synch data between clients to allow for networked objects (Section 3.2.2). Figure 7 visualizes the interconnected systems between the client, server, and the Circles API. The WebSocket messages are small textual JSON objects that
allow synchronization of events between clients in collaborative activities. In the future, we would like to explore how to limit WebRTC P2P traffic to better scale to more users than the approximately 10-15 that Circles’ can currently handle, though we would have to create larger VLEs with more virtual space for users to spread out to comfortable distances [84]. One solution would be to use more powerful server computers. We may also have to look at “level-of-detail” strategies where not all data must be sent to everyone, depending on distance away, for example.

![Figure 7. Circles’ client-server system architecture. The JavaScript server serves both 2D and 3D/WebXR pages, and the Circles API adjusts selection and navigation types depending on the platform the content is being served to. Note that under Selection, Presentation, and Navigation, DVR is desktop VR, MVR is mobile VR, and HVR is HMD VR. Though Circles is built on existing frameworks such as A-Frame (general WebXR library), Node.js (server), and MongoDB (database), we will several Circles API, components, VLEs, VLAs, and interactions to join all these systems together for more inclusive social learning in VR.]

3.8 Implementation

Here we detail the server and client design of Circles. Circles’ client side is structured similarly to the entity-component systems employed by A-Frame. ECS makes it easier for
developers familiar with A-Frame to understand how to extend Circles’ functionality and transition to Circles development. All Circles’ worlds are in a single folder with an index.html file, associated assets, and Javascript files. Developers use JavaScript for client files, the server (Node.js), and the database (Mongo) for consistency across the client and server codebases.

### 3.8.1 Server-side

We use Node.js and a Mongo database to serve all web pages and handle login authentication. Additionally, we separate webpage routing and server-side functionality into separate files, e.g., adding or removing users separately via router.js and controller.js files. We also added the ability to create "magic links" so that an instructor can send out learner web links to bypass the login page for greater accessibility. The instructor sets which worlds and groups learners log into. Additionally, the server relays data between clients (Section 3.2.2).

### 3.8.2 Client-side

On the client side, developers will use Javascript and HTML to build Circles' worlds. As noted in the server-side section, there are many elements to ensure that a web page connects to all of Circles' systems, e.g., multi-user networking, networking layers, Circles' components etc. To ensure that it is easy to create a world without an overwhelming amount of boilerplate code required, we use a simple search-and-replace system to "compile" Circles' web pages. Specifically, using Webpack [383], which bundles code into one file, we look for "Circles" tags within user-developed pages and then replace those tags with all necessary components required to include all Circles' functionality. The server then serves the compiled HTML page. The following code is what the simplest HTML Circles' "index.html" world looks like (the custom “circles-“and “circles_” tags will be replaced before serving the HTML page). Building on the below code, developers may add Circles' components, A-Frame components or create their components using Javascript.
3.8.3 Components

Developers can create components and use existing A-Frame-based components. Circles also provides several built-in components to support social interactions, to provide virtual learning artefacts, and to provide objects for simple selection-based interactions. It also includes some convenience components users requested while developing and testing Circles, e.g., 'circles-lookat,' which keeps a 3D object always facing the camera. The following is an example of what a circles-artefact component might look like in use. Following an ECS pattern, the A-Frame HTML element "<a-entity></a-entity>" is the entity, and the HTML attributes of that entity are the components, e.g. “<a-entity some_attribute><a-entity>.” Also, all Circles’ components, e.g., circles-artefact, use the glTF 3D model format as “glTF minimizes the size of 3D assets, and the runtime processing needed to unpack and use them.” [122]. The following code snippet is an example from one of the Viola Desmond worlds described in Section 4. It is an HTML element/entity with several attributes defining its basic visual appearance (position, rotation, scale, shadow, gltf-model etc.) and Circles’ specific appearance and behaviour (circles-artefact).

```html
<a-entity id="Artefact-Paper"

    position="1.64 0.52 0.64" rotation="-90.0 163 0.0" scale="0.01 0.01 0.01"
```
In the following list, we describe several Circles’ specific components that developers can use within their Circles’ worlds. Please note that this is not an exhaustive list due to space, but are several of the most significant components.

- **circles-artefact**: This core component explores learning around storytelling-based VLEs. The circles-artefact creates an object with text and audio descriptions that avatars can select and manipulate.

- **circles-button**: This is a general-purpose button that we can use to listen for click events and trigger our code or use in combination with another Circles' component, e.g., circles-sendpoint.

- **circles-checkpoint**: Attach to an entity the developer wishes to act as a locomotion checkpoint.

- **circles-description**: Used to create a sizeable rectangular object with text on both sides.

- **circles-interactive-object**: Attach to an entity that you wish to be interactive, and add visual feedback to the object, i.e., hover effects like an outline or highlight. Also, developers can add a sound effect for the click event.

- **circles-label**: Used to create a small visual label.

- **circles-lookat**: Attach to an object to have it always facing another element.
• **circles-networked-basic**: This component allows an object to be shared with other connected clients. It also attempts to handle cases when clients disconnect to avoid disappearing. Unlike the circles-pickup-networked component, circles-networked-basic objects are not directly interactive.

• **circles-pickup-object**: This component lets you select, manipulate, and release objects on click.

• **circles-pickup-networked**: This component allows the _circles-pickup-object_ to be shared with other connected clients. It also attempts to handle cases when clients disconnect and remove the duplication behaviour of Networked-Aframe objects.

• **circles-portal**: A simple component that creates a sphere that can be used as clickable hyperlinks to jump between virtual environments.

• **circles-sound**: This component extends A-frame's sound component and connects to the Circles’ “enter experience” user gesture, i.e., a user must click on a web page to autoplay sound and video.

### 3.8.4 Networking

The Networked-Aframe library and the Socket.io WebSockets library handle networking in Circles. Networked-Aframe uses WebRTC (to allow high-bandwidth communication like voice) and Socket.io to synch avatars and send messages. Circles abstracts much of this functionality to make it easier for developers to create social experiences. With the Circles components circles-pickup-networked and circles-networked-basic, developers can create objects all clients see without additional Javascript code. We also introduce a communication layer that provides Javascript events and functions to pass data between clients, sync elements, and create custom social interactions. Below, from the "campfire" world, this code snippet allows any user to turn on and off the fire to sync this campfire on or off state with other connected clients (Figure 2), and is an example of the `{data structure}` expected when sending a message from one client to another (developers can
use the CIRCLES global constant to access commonly used variables and methods within the Circles framework).

Here, the developer adds a message is sent to all other connected clients that the campfire has been turned on:

```javascript
CIRCLES.getCirclesWebsocket().emit( this.campfireEventName, { campfireOn:this.fireOn, group:CIRCLES.getCirclesGroupName(), world:CIRCLES.getCirclesWorldName() } );
```

Here, the developer adds an event listener to determine if someone else has clicked on the fire so that we can sync with clients.

```javascript
CIRCLES.getCirclesWebsocket().on(CONTEXT_AF.campfireEventName, function(data) {
    this.turnFire(data.campfireOn);
    this.fireOn = data.campfireOn;
});
```

### 3.9 Case Studies

This section will briefly describe several Circles' worlds created by developers with observations made during their creation to help showcase how Circles’ evolved through developer feedback.

**Viola Desmond (2019)**

![Figure 8. Developers created three Circles' worlds to describe Viola Desmond's story.](image)

Viola Desmond was a significant Canadian Civil Rights pioneer, and developers chose to help tell her story during the initial design and development of Circles [306]. The original HMD targeted was the low-powered Oculus GO [294], with one controller and no positional tracking. Thus, much of the initial work focused on optimizing worlds for low-
powered devices, simplifying interactions, and defining a 3D asset creation workflow. During the Desmond worlds’ creation, it was discovered that selecting VLEs was engaging, so we developed the "circles-artefact" component.

Women in Trades (2021)

Figure 9. Developers created three Circles' VLEs to highlight the challenges women may face in the trades.

Designed for a case study highlighting women's challenges in entering the trades, we focused HMD VR development on the Meta Quest 1 after the Oculus GO was discontinued. Developing assets for a more powerful HMD also allowed us to create higher-resolution textures and 3D models to describe each of the VLEs developed. Building these scenes taught us how to work with the community to design VR content and better refine Circles' documentation, components, and content creation pipeline to create engaging VLEs and VLAs. A full paper detailing the results of a study conducted using this environment is under preparation by the authors.

Kinematics (2022)

Figure 10. Developers created three different Circles' VLEs to help introductory physics students understand basic kinematics.

These VLEs were developed by non-Circles developers for an introductory physics class to understand kinematics with three standard experiments. The developers were creative in building around the performance limitations of mobile devices by using colour, text,
and simple geometry to highlight each of the three VLEs created. This project's development helped refine the Circles' framework to include desired functionality, such as the aframe-physics library, to make implementing the "naïve physics" [159] of reality-based interfaces straightforward to implement into any VLE easier. This physics VR content was designed under the supervision of a Physics instructor, with plans to be used and evaluated within their course.

**Research Projects (2023)**

![Figure 11. From left to right, three studies use Circles to create a symbolic memory palace for an introductory cognitive science course, a community co-design study with a local indigenous group, and a virtual recreation of a university campus.](image)

A Circles VLE was created for use within cognitive science classrooms to help students better understand the form and function of parts of the brain as illustrated metaphors [31]. Another world was created in collaboration with a local indigenous group to explore how to create VR content collaboratively [402]. And the last world is an early-stage recreation of a university campus. These projects helped us better understand how to support new-to-Circles developers. They were essential in helping us better document the setup process and to identify new Circles’ components for development, e.g., circles-lookat for having flat 2D illustrations always rotate to face the observer.
As part of a pilot into having other developers use Circles to create various learning-focused worlds, several small student groups of four or five members created space-themed, VR-themed, and AI-themed worlds throughout a semester term project. For many of these students, this was their first experience with using A-Frame and Circles to develop content, and for others, their first introduction to creating VR experiences. While observing development, we learned we should further abstract networking functionality and JavaScript coding principles to make implementing more complex and exciting multi-user collaborative interactions easier. The findings from student developer experiences will be the subject of another paper after another round of in-class use for Circles. However, we note some preliminary themes found in Section 5.
Other Worlds (2020-2023)

Developers created several other Circles worlds to help showcase how to use various networking and interaction components from the framework and to perform remote empirical studies [184, 307]. These included creating a Fitts' law selection and search system that allowed developers to capture technical data (time and the number of errors) during several experiments (far right). The development of these worlds helped us better explain how to use Circles’ components while also exploring the ability to have different users with associated privileges and roles, e.g., data-collecting researchers and participants.

3.10 Evaluation

To help with further understanding of how developers used Circles, we conducted semi-structured interviews with eight creators that used Circles to build the "research projects" (Section 4.4) and "student developer projects" (Section 4.5). All participants were university students aged 20-23 (3 men, 5 women). We recorded answers via notetaking and analyzed content post-study looking for themes with an emergent coding approach [60]. Though the study is preliminary, it helps us set future development objectives to improve the usability of the Circles framework for developers. We scheduled a one-on-one remote videoconferencing session with each participant to ask the following five questions to understand their experiences:
1. What is your general/overall impression of using the Circles VR learning framework?

2. How easy/difficult is the framework to use?

3. How does using Circles compare to creating educational Virtual Reality development without the framework?

4. What features would you like to see added/modified?

5. Any additional comments?

Positive themes identified included "easy-to-use," "fun," "helpful components," "liked example worlds," and "would use it again." Negative themes identified were "debugging difficult," "compilation long," "installation difficult," "documentation incomplete," and "content creation challenging." Most developers found the framework easy to use if they had previously used A-Frame. However, two participants said they found it difficult to internalize the design patterns of the Circles ECS system, which is likely due to having limited experience with A-Frame or Unity, which both also use an ECS coding pattern. Another common theme was that the documentation provided was helpful but did not sufficiently cover all aspects of the Circles system, leading to confusion about adding custom functionality. Participants found that the included "example worlds" helped their understanding and suggested tutorial videos.

All participants found Circles fun and were surprised at how easy VR development can be using HTML and Javascript. However, three participants lamented the difficulty of setting up Circles initially with node.js and Mongo, even with the step-by-step instructions, due to the many systems required. One participant suggested a more straightforward solution using Docker, where a script could install all aspects procedurally [77]. The major pain points throughout development came from content creation, where creating or importing 3D models led to strange scaling, lighting, and performance issues depending on which 3D modelling software was used or where developers downloaded models from. For example, if a 3D model had too many polygons or high-resolution textures, the browser would run out of memory and crash. A-Frame and Circles’ reliance
on glTF models were noted as challenging, as not all 3D modelling software, like Autodesk Maya, supports the emerging 3D format. This complication led to developers switching between different software to export to glTF models. The glTF issues were compounded when developers exported models with too many polygons or high-resolution textures that could not be displayed on lower-powered mobile devices and had to be re-topologized and re-exported.

All participants had feature requests centred around making networking easier (as many focused on single-player experiences and often "didn't explore multi-user stuff as much"), easier to debug, and more documentation. More specifically, they enjoyed the networked avatars and artefacts. Still, they wish they had “spent more time understanding” other networked components and the messaging system to create more interesting collaborative interactions.

3.11 Discussion and Future Work

Circles provides a VR learning framework for increased engagement and inclusion while exploring alternative learning foundations and alternative VR learning frameworks. Looking back at our research questions, we can make some observations about the present and future of Circles’ VR learning framework.

1. How can we build a VR framework to increase engagement and inclusion within VR learning activities?

Increasing features while retaining a simple and usable interface and interactions across three dramatically different VR platforms requires striking a delicate balance between developer usability and framework flexibility. Still, Circles provides a solid base for further research and development by focusing on the guiding principles of platform scalability, social scalability, reality scalability, interaction scalability, and information scalability. However, we need to explore further the accessibility of other interactions, such as viewpoint control [6] and include more standard web accessibility features, such as contrast and colour adjustment, and text reader support, in addition to exploring other
locomotion methods for shared social learning spaces [114], and more immersive interactions, e.g., hand-tracking for controller-less HMDs [154].

2. How to make it easier to create VLEs and VLAs that encourage communication, collaboration, and critical thinking within a transformative learning context?

From our case studies and developer interviews, we argue that Circles shows promise as a VR education framework accessible to developers and promotes more transformative learning with axis worlds, such as the campfire, creating a virtual space for processing and reflection activities. Additionally, Circles’ artefacts and networking layer help objectify knowledge to support learners’ inclinations to share, communicate, and collaborate. Still, further formal real-world case studies of the platform in social learning spaces will be necessary, e.g., using Circles in classrooms and museums to more formally evaluate whether communication, collaboration, and critical thinking skills are being enhanced, and if they are, in what ways do the different VR platforms mediate this. It is not always clear that HMD VR is better than lower immersion VR for learning [211].

3. How do alternative learning methodologies considering a socio-cultural pedagogy change the foundation for VR design decisions within social learning spaces?

By focusing on a pedagogy that considers how individuals’ learning is interconnected with their immediate community, environments, artefacts, tools, and learning outcomes, we can create a more comprehensive use of VR for learning across physical and virtual worlds. Circles enables these connections by focusing on creating interactions mindful of our physical spaces with low-effort symmetric selection interactions and multi-platform VR support to acknowledge social anxiety. Additionally, Circles’ focus is on virtual learning artefacts that can move between different Circles’ worlds, helping to share knowledge and allow unique social interactions – suggesting that VR can be both a physical tool and a medium for containing digital tools. There is an immense challenge in creating a virtual reality that can parallel a physical reality without replacing it, but Circles’ provides a solid foundation for exploring these connections further into social learning spaces such as classrooms and museums and how, perhaps, we connect them in a way where we enhance their learning effects without trying to replace them.
In our case studies and during development, we have noted several areas worth pursuing in improving Circles, such as easier installation, better documentation, better guidance on debugging HTML and Javascript and enhancing performance with non-performant 3D content. There is ongoing exciting research in social VR [212], suggesting that supporting non-verbal communication is essential. Another avenue for further consideration is addressing privacy concerns, for example, to offer improved control on whether learners need to interact with others if they wish to explore alone [390]. Additionally, better defining how learning outcomes in VR spaces are met could be helped by exploring methods of assessments within VR [253, 288]. Furthermore, allowing even greater personalization around VR controls, e.g., supporting hand-tracking for future HMDs that ship without controllers [154] and allowing more avatar customization, could help keep learners engaged. Continuously working with developers to better understand the development bottlenecks is necessary, as is performing additional studies into how new users use and develop using Circles. There is interest in making networked activities easier to use. E.g., instead of providing a raw messaging layer for synching clients, there could be more components like circles-pickup-artefact that allow automatic synching between clients. A more robust networking layer could be extended into other collaborative activities, such as solving multi-user puzzles and asynchronous interactions that will enable the VLEs to be modified for others to find those changes later.

3.12 Conclusion

We presented Circles in this paper, an open-source WebXR-based framework for creating more inclusive and engaging VR learning environments. We described its core concepts, features, interactions, and implementation as an example of a VR learning framework that focuses on creating a stronger foundation for experiential learning from a socio-cultural pedagogical perspective. With this foundation, Circles provides a framework that focuses less on presentation and re-creating our physical learning spaces and more on authentic VLEs and VLAS to encourage discussion, reflection, critical thought, communication, and collaboration. Through several case studies and developer interviews, we can conclude that Circles is pursuing a fruitful direction toward a practical VR learning framework. Additional research and development will increase the accessibility and
efficacy of social features for developers and create better documentation, debugging, and installation tools. We hope that Circles provides an exciting alternative to trying to re-create VR presentation spaces that we see from many others. We look forward to furthering its accessibility, inclusion, practical use cases, and enhanced social features in the future.

References

[Aggregated at the end of this thesis]
“First-person gestural interfaces work best as an extension of the user’s body when the controlled device is anthropomorphic. Otherwise, an additional layer of interface is required and might call on another point of view altogether. Sometimes giving the user the ability to swap between views may accommodate different tasks.”

Nathan Shedroff and Christopher Noessel
Chapter 4: Exploring Selection and Search Usability Across Desktop, Tablet, and Head-Mounted Display WebXR Platforms

This chapter has been published (or submitted) as a journal (or conference) paper:


4.1 Introduction

Virtual reality (VR) technology has advanced significantly in recent years, resulting in widespread applications [111, 246, 379], novel research endeavours [123, 265, 273], and promising learning opportunities [112, 289, 309]. Our research focuses on using VR in social learning spaces, where users learn together or alone across physical and virtual realities, such as classrooms and museums. These social learning spaces can use physical and digital tools to re-create more authentic, engaging, and transformational learning experiences [309]. However, many challenges remain in using VR in social learning spaces, where accessibility is critical [78, 175]. Head-mounted displays (HMDs) are currently the predominant VR platform today, and yet, several limitations of HMD-based VR limit access to the technology. These include cybersickness [121, 243, 309], social anxiety from unfamiliar technology [269, 390], not having the physical means to "grasp" virtual objects [245], or the space to walk around in virtual environments (VEs) [192, 311]. Since learning requires an inclusive and accessible approach, we argue that VR-based education applications must support multiple hardware platforms so users with varying abilities, experience, and technology access can still benefit from VR. Notably, some VR learning applications support desktop and HMD-based VR in recognition of this goal [90, 196, 403].

Some multi-platform VR systems support desktop, mobile, and HMDs. However, there has been relatively little research in this area, especially on mobile platforms where a handheld device acts as a window or "portal" [209] into a VE. Designing usable VR applications is challenging due to the lack of 3DUI standardization, personal preferences, physiology, and user psychology [190]. These challenges are compounded in systems that adapt across various displays, devices, and inputs. A multi-platform VR approach to
social learning spaces is essential [309] as many post-secondary institutions embrace a Universal Design for Learning (UDL) approach [25], where learning content must be accessible from a variety of modalities [175].

Previous multi-platform VR research has shown that users strategically change between VR platforms for learning depending on the task [403]. Yet, currently, the only VR platform that natively supports desktop, HMD, and mobile VR is WebXR [386]. However, there is little empirical evidence comparing the relative performance of the three platforms supported by WebXR (desktop, mobile, and HMD) or if the performance of the individual platforms is in line with non-WebXR studies in VR interaction. In addition, many developers and HMD manufacturers are now working towards better supporting WebXR applications such as Mozilla Hubs [246] and FRAME [111]. Yet, without comparative studies of WebXR's platforms and frameworks that make it more accessible, the relative effectiveness of each supported platform is unclear.

Our study consists of three parts: 1) a selection experiment, 2) a search experiment, and 3) a virtual learning environment (VLE) exploration experiment using selection and search techniques from earlier in the study. To narrow the scope, we focused on selection and search in VR. This has the advantage of enhanced experimental control while focusing on the technical interactions of selection and search. The most common VR interactions include selection (target acquisition), manipulation (changing the pose of objects), and navigation (moving through an environment) [38, 194]. In practice, many systems employ selection-based metaphors for both manipulation (e.g., remote pointing to move objects [194]) and navigation (e.g., selection-based travel via pointing at a location to teleport [194]). Selection-based travel often requires the environment to include selection targets that the user points at to teleport around space. These selection-based interaction methods are beneficial as they reduce the physical movement required of users [121, 194, 309]. Moreover, they align well with the capabilities of various platforms. For example, selection-based interaction can be used with an HMD controller (remote pointing), a desktop mouse (clicking selection targets), or a mobile touchscreen in mobile VR. Existing selection techniques can be leveraged to make selection more accessible [104, 370]. This is critical in social learning spaces where we cannot assume
all users have the physical space and abilities to use more immersive interaction techniques [309]. We are unaware of past studies using WebXR to compare platform capabilities beyond desktop and HMD VR.

We aim to quantify performance differences between WebXR platforms and determine if they align with past VR selection and search studies. However, our study focuses less on including the distractor objects required for the formal definition of "visual search" [394] and more on the mechanical ability to orientate a viewport to select a static target from in and out of the user’s view. Though visual search is the closest parallel, to avoid ambiguity, we will refer to our search task as "search" rather than "visual search." The quantitative performance evaluation part of our study consists of 1) a target selection experiment following a 3D extension [362] of Fitts' law [106, 208] employing the ISO 9249-9 standard [415] and 2) a search experiment in a basic VE, without distractors, to test general usability of look controls (Figure 16). These two tasks frequently occur in most VR applications and are essential in learning applications. Note that interactions in our study employ the default display/controller interaction configurations provided by the A-Frame WebXR framework [7]. The HMD is paired with motion controller "laser controls," which use a ray cast from the controller to intersect with and select virtual objects, e.g., virtual objects and teleport checkpoints and HMD orientation for viewport orientation. The mobile conditions use finger-based tap for selection and device orientation for viewport orientation. In contrast, the desktop uses the left mouse click for selection and mouse drag for viewpoint rotation.

After selecting and searching, participants completed a more qualitative and holistic exploration experiment within a VLE. All interactions in this part used the same selection and search techniques practiced in the first part of the study. The VLE walk-through is an example of an unguided learning activity [368] created for a gender diversity workshop (Figure 15). Finally, we collected subjective data via several questionnaires, including a self-consciousness scale (SCS) [313], NASA-TLX [252], the Intrinsic Motivation Inventory (IMI) [153], focusing on subjective and personal differences between platforms, and a System Usability Score (SUS) to capture general usability [42]. We also used a Slater, Usoh, and Steed (SUS) presence questionnaire [374]. Although it is not
recommended for vastly different platforms, presence is not a focus of this study. The SUS questionnaire provided a basis for a difference between platforms. While the primary goal of our research was to compare the VR platforms, the follow-up part contextualizes our work within learning research and draws linkages between learning outcomes and quantitative performance metrics.

The study used the open-source Circles WebXR learning framework [308], built with A-frame, as Circles aims to reduce interactions, such as navigation and object manipulation, to symmetric (working similarly regardless of VR platform) [103, 308] single selection actions across all supported WebXR platforms to make them more "simple and intuitive" [365].

Our research questions include the following:
1. What are the differences between the desktop, tablet (mobile), and HMD WebXR in terms of selection and search performance, and usability? Are these differences consistent with prior multi-platform VR performance studies?

2. Does multi-platform WebXR, specifically the Circles framework, show potential for usably supporting learning activities within social learning spaces?

Our hypotheses:

RQ1. Selection performance (in terms of selection speed and error rate) will be best with desktop, then mobile, then HMD.

RQ2. Search will be fastest with the HMD due to the larger field of view and natural head movement orientation, then desktop, and slowest with mobile.

RQ3. Performance results will be similar to past studies.

RQ4. Circles, and WebXR more generally, will show potential for learning in social learning spaces.

4.2 Related Work

Several environmental constraints exist when discussing the performance and usability of a multi-platform WebXR framework within a social learning context. Specifically, when learners use a VR device, the experiences should have interactions that allow for rich interaction within a physically stationary (non-moving) position. Furthermore, these interactions should be simple and intuitive across all supported platforms [365]. Within this context, we can reduce most complex interactions to their fundamental "selection" and "search" forms.

4.2.1 Selection Studies

VR interactions fall under three main categories: selection, manipulation, and travel [38, 194]. Furthermore, selection and manipulation techniques are classified into six interaction metaphors. These include grasping (e.g., using a virtual hand), pointing (e.g.,
ray-casting), surface (e.g., using a 2D multi-touch surface), indirect (e.g., a ray-cast selection and multi-touch gestures to modify without directly selecting the object of interest), bimanual (using two hands to interact), and hybrid interaction techniques that change depending on the context of selection [194].

Selection studies often compare performance between various input and display methods, i.e., comparing varying mouse gain values on desktop [366], pointing task performance with "fish-tank" VR [363], and comparing head-based and eye-based selection tasks [287]. Fitts' law – a human performance model of rapid aimed movements – is frequently employed for studying 2D selection. There are several proposals for using Fitts' law in three dimensions. These include discussions on target properties in 3D selections using virtual hands [354], the development of new models for more accurate predictions on pointing selection tasks [181, 404], and research into extending Fitts' law to incorporate depth [57] through both translation and rotation [353]. Many studies have validated Fitts' law across decades of HCI research [338].

Figure 16. The most common forms of Fitts Law selection studies (left) utilize a simple pointer device, and the user selects the center vertical target, moves from one side to the next, and back again for n number of trials. The 2D form (centre) asks the user to select targets number 1, then 2, and so on for n trials where the user can move in both the vertical and horizontal direction. The 3D version (right) is similar to the 2D version but requires a pointer device, i.e., a laser pointer. Due to the use of a "laser/ray-casting" pointer, the angular (rotational) distance (deg) is used to determine the width of targets (ω) and distance between targets (α). This study uses 2D and 3D forms.
4.2.2 Fitts' Law

As selection is one of the most prominent interactions across 2D and 3D contexts [194], many studies have investigated the selection performance difference between various input and display modalities. To standardize experimental design and improve consistency between study results, Fitts' law [106, 208] is widely used for studying selection performance by comparing the "transmission of information" [147], represented via the throughput metric (bits/second) [106, 181, 319].

Fitts' law was initially developed for 1D contexts [106], where movement time is recorded as participants repeatedly select two vertical targets (Figure 16, left). Fitts' law was later re-purposed for 2D contexts where several targets are arranged in a circular pattern. Users select each target in a clockwise sequence, moving from one side of the circular arrangement to another (Figure 16, centre). For 3D tasks employing ray-casting to select remote targets, Fitts' law has been modified to quantify distal pointing tasks [181, 353].

Fitts' law is a predictive model of target selection time based on the distance to and size of the target. The log term in Equation 1 below is the Index of Difficulty (ID); this variant presents the "Shannon" formulation of ID [319, 338] commonly used for 2D selections, e.g., selecting targets on a flat screen:

\[
ID_{2D} = \log_2 \left( \frac{A}{W} + 1 \right)
\]  

(1)

ID\textsubscript{2D} is the Index of Difficulty for a 2D selection surface, where A refers to the amplitude or distance to the target, and W refers to the width of the selection target. However, distal pointing involves selecting targets within an immersive virtual or physical 3D space (e.g., selecting virtual targets within an HMD or selecting targets on a screen using a physical pointing device). This should consider rotation movements of the wrist and arm [181], which better reflect user movement to reduce arm fatigue or the "gorilla-arm" effect [144]. Though several formulae are used to describe Fitts distal pointing tasks [181, 338, 353], we focus on Kopper et al.'s form, which considers the rotation-based motions of our joints naturally [287]. However, the relationship between translational and rotational
movements is not always clear in 3D tasks [371]. The formula for calculating angular distance follows [181, 353]:

\[ ID_{\text{angular}} = \log_2 \left( \frac{\alpha}{\omega^k} + 1 \right) \]  

(2)

where \( \alpha \) is the angular distance from the starting point to the selection target, and \( \omega \) is the angular width of the target. The term \( k \) describes a non-linear relationship between \( \alpha \) and \( \omega \), as target selection often involves two phases – ballistic and correction [181, 202].

A primary component to facilitate objective comparison between conditions is the throughput measure (TP). Throughput is a standard measure for understanding the relationship between ID and movement time (MT) across various selection inputs. The formula for TP is as follows [338]:

\[ TP = \frac{ID}{MT} \]  

(3)

4.3 Search Study

Identifying an element or target within a virtual environment is crucial for exploring and navigating VEs. More formally, Visual search tasks "determine if a specific target item is or is not present among the distractor items" [394]. Visual search tasks are an intrinsic part of VE navigation, such as wayfinding, whereby a user must understand their place within a VE and be able to plan a route through it and the travel or movement through the VE itself [194]. Most strategies include landmarks [320] but other techniques, such as having overview or "view-in-view" maps [395] and may incentivize participants through means such as finding the exit in a virtual fire [45]. Search tasks are essential for finding objects, points of interest, or landmarks within VEs and VLEs, such as virtual museums.

Several studies investigate search performance across various factors. For example, studies assessing search performance under different display field of view (FoV) conditions have shown that FoV, and target movement from out of view, plays a vital role...
in allowing users to find targets [134, 255], though perhaps not enough of an effect to help train for real-world scenarios [291]. Additionally, head-rotation amplification may aid search tasks [290]. Some studies also suggest that audio cues may help users find targets, particularly those outside the FoV of the display [107]. At the same time, other researchers have investigated the use of search tasks to help with neurorehabilitation [178]. However, in all noted studies, there appears to be no standard form of assessing search performance, as there is for selection tasks and Fitts' law. In addition, many studies are performed within complex VEs or information-rich virtual environments [255], often as virtual recreations of real-world spaces.

4.3.1 Multi-Platform VR

Very few modern VR frameworks support more than one platform (e.g., supporting mobile and immersive HMD VR). The only real exceptions are the WebXR-based Mozilla Hubs [246] and Frame [111], which support VR across several platforms - desktop, mobile, and HMD. In addition, some social VR experiences, such as VRChat [61], have desktop clients to increase participation in social VR experiences, as exclusive HMD-supported applications appear not yet commercially viable [364].

In multi-platform research, studies suggest that HMD VR performs better than desktop VR for 3D navigation tasks within a maze using smooth locomotion [339]. One study found participants perform better using desktop VR over HMD VR for spatial tasks [58], which aligns with other results showing significant differences between desktop VR and HMD VR in the gazing behaviour of participants [102]. Still, the differences were negligible in the wayfinding plans detailed at the end of the study [102]. Another study examines the differences between tablet and HMD AR for 3D selection performance, finding the HMD less fatiguing [277]. However, we could not find studies comparing desktop, tablet, and HMD VR simultaneously, though these VR platforms are highlighted by early researchers in the VR field [43].

With the exploration into more accessible VR and APIs such as WebXR natively supporting multi-platform VR, there is potential to explore multi-platform VR research, even if many implementations currently do not support mobile well and may have
usability and technical issues [90, 403]. Additionally, there is evidence that supporting multi-platform VR allows individuals to switch between platforms to use better each platform's advantages and disadvantages, such as higher presence and focus with HMD VR [196, 403] and better multitasking with desktop VR [403].

4.4 Methodology

Our investigation consisted of three separate experiments. The first and second focused on selection and search within a simple virtual environment to avoid distractions. The third experiment was an open exploration to investigate general usability in a simulated VLE as a more authentic use case. Initially designed as a lab-based within-subjects study to compare three VR platforms – desktop, tablet (mobile), and HMD- we switched the study to a between-subjects remote study during the COVID-19 pandemic [62] shut down university campuses. A between-subjects design allowed us to recruit participants that only required one of the three VR platforms rather than all three. We scheduled 45-minute meetings with recruited participants via video calling for communication. We used a web-based social VR platform called Circles [308] and an associated "research VE" (Figure 14) we developed for connecting with participants as virtual avatars with their given VR platform. We performed the selection and search tasks within the research VE for each participant, collecting performance data (time for target selection and the number of times a selection target is not correctly selected). For the third part of the study, we asked participants to explore a VLE more informally and its three virtual learning artefacts (VLAs) in Circles, asking them to talk aloud so that we could capture notes about their exploration and experience of the virtual environment.
Figure 17. A time-based flowchart of our three-experiment study.

4.4.1 Participants

We recruited a total of 45 post-secondary students (18 female, 23 male, 3 non-binary, and 1 did not answer) between the ages of 18-44 (M = 26.93 years, SD = 7.64 years), with 15 participants assigned to one of each VR platform – desktop, mobile, or HMD. All participants were technically inclined and aware of VR, though many had not personally tried HMD VR.

4.4.2 Apparatus

For all HMD users, we lent out Oculus [Meta] Quest 1 HMDs. For 8 of the 15 mobile participants, we lent out a 10.4" Samsung Galaxy Tab S6 Lite tablet (the others used various personal tablet devices). We had 15 HMD devices and two mobile tablet devices that we could lend out, and each device was sanitized, dropped off, and picked up at each participant's residence. Each participant with a borrowed device had it for approximately two weeks (at least one week before the study to have time to set up and troubleshoot any issues with the researcher). All desktop participants used their own devices.

Most of the tablets used were 10 in. Apple iPad tablets and most desktop systems used 21.5 in. 1920x1080 displays with a standard mouse and keyboard. We recorded display resolution, pixel density, and scale to calculate target sizes across this study's various personal tablet and desktop screen sizes. The complete study consists of three experiments, each composed of multiple unique tasks: selection tasks, search tasks, and
open-ended exploration tasks that ask the user to select and manipulate three VLAs (Figure 15). For selection tasks, the participant selects each target displayed one at a time. This employs a predictable pattern crossing the circle of targets with each subsequent selection as recommended by the ISO 9241-9 standard (Figure 16, centre). E.g., the participant would click each circle/target highlighted in orange as it appears clockwise around the circles seen in Fig. 1 right (changing to various target widths and depths), and the Circles apparatus would capture and record the time of selection of the number of errors to a spreadsheet file the researcher can downloads at the end of the experiment to analyze post-study.

Upon completing the selection experiment, the participant starts the search experiment. Targets were displayed one at a time around the participant to find and select in the same research VE (Figure 14, right). After all targets are selected, the participant is asked to follow a web link for a post-test questionnaire. In the final VLE Exploration experiment, the participant is introduced to a single VLE recreation of a college electrician's lab created for a women in technology workshop (Figure 15). We asked participants to explore the VLE and select and manipulate the three VLAs present (a drill, a clipboard, and a pair of safety gloves). Next, the researcher asks the participant to talk aloud about their thoughts on the VLE, interactions, feelings, sounds etc., in real-time. The researcher recorded these thoughts as observer notes. Finally, we gave the participants another survey link to follow and complete a post-experiment questionnaire. At the end of the experiment, the researcher asked if they had any questions and solicited any further participant feedback. Throughout the study, the researcher frequently asked how participants felt about pausing the experiment and if participants experienced any discomfort. All participants completed the experiment with minimal issues.

4.4.3 Procedure & Design

The first experiment is a between-subjects (VR platform) 3×3×3 Fitts' law selection experiment where the independent variables are the input method (desktop, tablet, HMD), target width (0.25m, 0.5m, 0.75m), and depths – z-distance from participant to target (5.0m, 7.0m, 9.0m). Our dependent variables included selection time (ms), error rate (%
of targets missed), and throughput (bit/s) calculated as described in Equation 3, Section 2.1. Each condition included 16 trials, i.e., individual target selections. In total, participants completed a total of 3 platforms × 3 target widths × 3 depths × 16 trials × 15 participants for a total of 6480 selection data points.

The second experiment is a between-subjects (VR platform) 3×3 search experiment where the independent variables are the input method (desktop, tablet, HMD), x-axis position (3 possible positions), and y-axis position (8 possible positions). Each condition included 4 trials. In total, each participant completed a total of 3 platforms × 3 x-axis positions × 8 y-axis positions × 4 trials × 15 participants for each platform for a total of 4320 total search data points (some data points failed to capture due to a minor bug we fixed later, so the actual total is 4198). Figure 14, right depicts all search targets positions. Our dependent variables included selection time (ms) and error rate (% of targets missed). After the selection and search experiments, participants filled out a post-test questionnaire capturing the self-consciousness scale [313], NASA-TLX [252], the Intrinsic Motivation Inventory [153], and SUS presence [374].

For the open usability experiment, participants used the selection and search techniques they practiced in the first two tasks to explore a complex VLE created for a gender diversity workshop (Figure 15) and select and manipulate (using selection-based techniques) three VLAs found within. We felt that exploring this space in an informal and unguided manner best followed a learning activity that instructors may ask their students to explore inside or outside of classrooms for a few minutes, and we wanted to keep an open mind to how participants would use the Circles framework and explore the associated VLE. This concept aligns with Circles' proposed objective of not replacing classrooms but instead acting as a learning tool alongside other more traditional analog and digital teaching methodologies [308]. After the open usability experiment, we captured general usability with a questionnaire capturing the System Usability Score [42].

4.5 Results and Analysis

We describe the results for each of the three tasks below.
Table 8. Results for the Selection and Search Studies

<table>
<thead>
<tr>
<th>Platform</th>
<th>Select. Time (ms)</th>
<th>Select. Error %</th>
<th>Select. ID</th>
<th>Select. TP.</th>
<th>Search Time (ms)</th>
<th>Search Error %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Desktop</td>
<td>795.99</td>
<td>0.066</td>
<td>4.22</td>
<td>5.80</td>
<td>2472.60</td>
<td>0.17</td>
</tr>
<tr>
<td>Tablet</td>
<td>829.35</td>
<td>0.15</td>
<td>4.19</td>
<td>5.63</td>
<td>3301.36</td>
<td>0.30</td>
</tr>
<tr>
<td>HMD</td>
<td>1099.98</td>
<td>0.12</td>
<td>4.49</td>
<td>4.40</td>
<td>2830.85</td>
<td>0.12</td>
</tr>
</tbody>
</table>

4.5.1 Selection Performance

One-way ANOVA detected significant differences in selection time (F1,45 = 17.65, p < .05) and throughput (F1,45 = 8.85, p < .05). Tukey-Kramer HSD post hoc tests revealed that the HMD was significantly worse than the tablet and HMD platforms. We found no significant differences in the number of errors and thus do not report statistical results. The average error rates in Figure 18 are in ranges expected from similarly designed Fitts' law experiments [287].

The absence of a significant difference between desktop and tablet and the higher-than-expected TP of desktop suggests that the variety of personal desktop devices introduced some noise into the experiment, reflected in the large standard deviations seen in Figure 18 (left). Still, the general themes align with past results demonstrating superior performance with desktop input over VR-based input [338]. In general, 2D-based direct manipulation techniques offered better performance than the 3D motion controllers, likely due to a combination of arm fatigue and complexity from the additional degrees of freedom required for control [160]. Typically, Fitts' law studies compare selection techniques on a single platform using consistent IDs across conditions. Using the IDangular calculation for the HMD yielded slightly different IDs than the desktop and tablet. The IDangular equation treats distance and width as angles measured in degrees (Equation 2, Section 2.1). This was necessary for the HMD distal ray-based pointing, as the usual ID formulation used for desktops and tablets uses straight-line distances (e.g., in pixels or cm, see Equation 1, Section 2.1). We note that we used a k value of 1.0 in our IDangular calculation for consistency with previous studies [287]. Changing k might have yielded IDs closer to those used with the tablet and desktop. However, as throughput results in the same units of "information" (bits/s), it still feels relevant to compare various
devices using it [338], even if the numbers do not align due to vastly different VR displays and inputs.

![Figure 18. Left: Throughput (bits per second) by VR platform. Errors bars show ± 1 SD.], Right: Linear regression model for all VR platforms, showing the relationship between ID and MT.](image)

![Figure 19. Search Time (milliseconds) by VR platform. Errors bars show ± 1 SD.](image)

### 4.5.2 Search Performance

One-way ANOVA revealed significant differences in search time (F1,45 = 8.63, p < .05) and in selection errors (F1,45 = 4.17, p < .05). Tukey-Kramer post hoc tests revealed that the tablet offered significantly worse search performance than either the desktop and HMD (Figure 19). This is likely due to the much smaller screen and the tablets. Search performance with the desktop and HMD were roughly the same and not significantly different. We will ignore the errors here as the only significance revealed by post hoc analysis was between tablet and HMD, suggesting that participants' more refined movements of using their fingers resulted in fewer errors than the gross motor skills required to use their wrist and arm to select targets with the motion controller connected to the HMD. Selection is also not the focus of the "search" study.
We also analyzed our post-test questionnaires (IMI, SCS, NASA-TLX, SUS presence) using the non-parametric Kruskal-Wallis test. We did not find significant differences between platforms for intrinsic motivation, interest/enjoyment (p = 0.25) or perceived competence (p = 0.25). In addition, we did not find significant differences between platforms in cognitive load using the NASA-TLX survey (p = 0.47). However, we did see a significant difference for the SUS presence questionnaire [374] (h(2) = 10.92, p = 0.0042). Furthermore, Dunn's posthoc test revealed that participant presence with the HMD was significantly higher than with either the tablet (p = 0.015) or the desktop (p = 0.0016). This was expected due to the more immersive qualities of the HMD, which likely enhanced presence. Finally, there was a significant difference between platforms for the public social consciousness scale (h(2) = 7.31, p = 0.025). Dunn's posthoc test revealed a significance between the desktop and tablet groups within the public social consciousness scale (p = 0.0067), where desktop scored higher than tablet. Public self-consciousness refers to a tendency to think about those self-aspects that are matters of public display, qualities of self from which impressions are formed in other people's eyes [313]. This difference suggests that participants were more aware of the researcher using desktop. This is likely because they used the same device to video chat with the researcher to complete the study. Whereas, with tablet and HMD, participants used a secondary desktop computer for video-calling and did not directly engage with the researcher during the study.

4.5.3 Open Usability Exploration

As seen in I, the main themes found in this part of the study were "Artefact," "Discussion," "Enthusiasm," "Learning Potential," "Navigation," "Personal Preferences," "Suggestions," "Surprising," "Technical Challenges," "UX Challenges," and "Virtual Environment." The VLAs and VLEs quickly become the focus, as the visuals were often described as "cool" and the detail incredibly "full," "more lived-in [which] … makes it feel like more my reality". The ambient sounds of exhaust fans and people's voices were noted often, with several participants commenting that they "love" the ambient sounds and the VLA's audio narration. The verbal narration of a first-person description of the
challenges they faced within the trades as a woman was appreciated as the narration "helped with reading" the mirrored text bubbles (Figure 15).

However, there were also several UX issues noted by participants. Selecting menu items was notably challenging to understand since being parented to the virtual camera often resulted in occlusion by objects within the VLE. Also, several artefact control items had unclear iconography. For example, the down arrow (bottom-middle button, under the held artefact in Figure 15) used for releasing or dropping a VLA was interpreted as a download icon and ignored. Many participants found the VLEs easy to navigate the virtual space using the teleport pads dotted throughout the room and mouse, tablet orientation, or HMD orientation to look around. However, there were many challenges beyond the UX issues. Some technical issues included Wi-Fi failing, audio issues, graphical glitches (e.g., a door not to scale), physical discomfort (e.g., HMD too heavy, holding a tablet for too long is difficult), and mild cybersickness. Some non-technical issues included "daily life" disruptions, such as cats scratching at the door, roommates talking in the room, and feeling uncomfortable wearing the HMD around others, suggesting feelings of social embarrassment [41].

Table 9. The qualitative data was analyzed in observation notes and open-ended post-questionnaire questions about the final "VLE Exploration" experiment in this study. First, with an expected set of thematic codes from our literature review (deductive), then adding codes found with data that did not fit easily or were surprising (inductive), we determined 11 central themes.

<table>
<thead>
<tr>
<th>Deductive Codes</th>
<th># of Refs.</th>
<th>Deductive Codes (cont.)</th>
<th># of Refs.</th>
<th>Deductive Codes</th>
<th># of Refs.</th>
<th>Deductive Codes (cont.)</th>
<th># of Refs.</th>
<th>Deductive Codes</th>
<th># of Refs.</th>
<th>Deductive Codes (cont.)</th>
<th># of Refs.</th>
<th>Final Themes (after the merge and sort of codes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Artefact UX Negative</td>
<td>56</td>
<td>Technical Challenges</td>
<td>11</td>
<td>Artefact Positive</td>
<td>3</td>
<td>Surprising</td>
<td>10</td>
<td>Artefact Suggestions</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Artefact UX Positive</td>
<td>4</td>
<td>VE Negative</td>
<td>0</td>
<td>Competitive</td>
<td>1</td>
<td>Unexpected Behaviour</td>
<td>5</td>
<td>Discussion Surprising</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Discussion</td>
<td>15</td>
<td>VE Positive</td>
<td>20</td>
<td>Gaming Experience</td>
<td>1</td>
<td>UX Positive</td>
<td>12</td>
<td>Enthusiasm Technical Challenges</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Enthusiasm</td>
<td>19</td>
<td>WebXR Novelty</td>
<td>3</td>
<td>Learning Potential</td>
<td>7</td>
<td>Navigation</td>
<td>7</td>
<td>Learning Potential UX Challenges</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction Negative</td>
<td>7</td>
<td>Presence</td>
<td>9</td>
<td>Social Embarrassment</td>
<td>1</td>
<td>Navigation</td>
<td>1</td>
<td>Navigation Virtual Environment</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Interaction Positive</td>
<td>5</td>
<td>Psychological Discomfort</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Personal Preferences</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Personal Preferences</td>
<td>10</td>
<td>Suggestion</td>
<td>22</td>
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<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Physical Discomfort</td>
<td>18</td>
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<td></td>
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<td></td>
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</table>
We also coded the observation notes and the post-experiment questionnaire data for the more complex "gender diversity" VLE (I)—much of the discussion centered around the UX, VLAs, and VLEs. Participants commented on challenges like being unaware of how to manipulate objects, e.g., not seeing manipulation buttons or not realizing they were for manipulation due to ambiguous iconography and lack of labels. Participants also appreciated the audio narration accompanying each artefact selection, although many found it challenging to follow audio narration while reading the simultaneously displayed text. We also analyzed our post-experiment questionnaire data using the non-parametric Kruskal-Wallis test. We did not find significant differences between platforms using the SUS usability test (h(2) = 10.92, p = 0.66), suggesting UX challenges were universal across all VR platforms.

4.6 Discussion

In this section, we summarize themes found in the study.

4.6.1 Selection Performance

Selection performance with each platform confirms hypothesis H1: the desktop performed best, followed by tablet and HMD, though our throughput scores appear high. As previously found [362], the familiarity and precision of the desktop mouse offered superior performance over the 3D controller [159], while tablet was a close second—the HMD ray-pointer controls required significantly more motor movements. Though these results are in line with past studies (hypothesis H3), we do note a discrepancy between our throughput scores, which are higher at 5.9 bits/s than typically expected of desktops (~3.7 – 4.9 bits/s) [338]. This higher performance may be related to the variety of personal desktop machines used, participant familiarity with their own devices and better hardware (e.g., gaming mice) not commonly employed in lab-based studies. While we collected display resolution and size, participants may have misreported. Screen-sharing to view participant computer settings would have helped, but we elected not to as it seemed an unreasonable privacy breach.
Additionally, our HMD ray-pointer results were also higher than expected [287, 362], suggesting that using the angular Fitts’ law equation (Equation 2, Section 2.1) may not capture all details in both rotating and translating during a distal pointing task, something noted by other researchers [371]. Additionally, Henrikson et al. found that Kopper et al.’s angular Fitts model did not match their data well [139], noting "this contrast to prior work warrants future investigation" [139]. The WebXR-based apparatus may introduce some unknown factors into the capture of selection time, but that also the use of ray-pointer evaluation within stereoscopic HMD VR is inconsistent.

4.6.2 Search Performance

The HMD and desktop offered the best search performance, confirming hypothesis H2. This is likely because of the naturalness with which users can look around an environment relying on the motion-sensing capabilities of the HMD. Many search studies focus on the ability to find targets in environments with distractors and varying specific variables, e.g., the FoV or rotation gain [107, 290, 291]. Our study focused mainly on the entire platform experience, each with a different FoV, rotation method, and interaction style. While these multiple variables make comparing platforms difficult, it has the advantage of being representative of how standard platform configurations would be applied in real-world scenarios. This facilitates a more holistic exploration of the challenges and opportunities for each platform within the associated WebXR frameworks.

The desktop represents the most common and likely most comfortable interaction style. This is especially true for more technically inclined participants, many of whom play first-person shooter (FPS) games. Conversely, the tablet requires one to hold the device as a "moveable window" into the virtual environment and search for targets in a much smaller window due to the smaller screen size. Although participants initially enjoyed the novelty of holding the tablet as a window into the virtual world, they soon grew weary of its weight. Due to the unique experimental setup, we cannot confirm if the search results align with previous work (hypothesis H3).
4.6.3 Insights and Themes

We captured several insights and themes through three experiments conducted with the same WebXR framework across several platforms (Table II). Much of this qualitative data was captured via talk-aloud discussion during the study as participants proceeded through the virtual environments. Though there is room for improvement, our observations support our hypothesis H5 that multi-platform WebXR and frameworks such as Circles can enhance and contribute to social learning spaces and thus show potential for learning activities, confirming hypothesis H4.

4.6.4 Usability

In general, usability was a significant weakness of the Circles framework. Misleading UI icons included an arrow used for releasing an artefact that was misinterpreted as downloading, the rotate button mistaken for a "browser refresh button," and the zoom button that looked more like a search button. Additionally, as users moved around the environment farther away, teleport targets' became smaller. As a result, they became hard to select using a pointer, as predicted by Fitts' law. An alternative cone cast interaction technique would reduce participant precision requirements relative to ray casting, e.g., selecting targets near a user's selection target.

There were also concerns about the text being difficult to read in VR, likely due to the low resolution of the HMD. Holding the tablets for extended periods was also uncomfortable. However, once participants were comfortable with the controls and could explore the VLE, most found the interactions usable. Also, as noted in Table II, there was a theme of "personal preferences," where some users preferred the option to have smooth locomotion, suggesting that having personalization could help advanced users' engagement.

4.6.5 Open Exploration

Generally, participant feedback captured during talk-aloud discussions demonstrated significant interest in using WebXR in their classrooms. Some participants noted reluctance for long lectures, however. Participants generally focused on the 3D visuals,
noting how they heightened their presence in the VLE. They were pleasantly surprised by the ambient sounds within the VLE, noting surprise, e.g., "I am a bit surprised that you can have VR on the web." Negative feedback surrounded artefact manipulation, as the UI wasn't clear about functionality.

Some HMD users also preferred a grabbing interaction. This suggests that a selection-only interface may work well across all platforms for accessibility but that more personal preferences should be available for advanced users. Several participants also found the content compelling, creating discussion around the VLAs and associated gender diversity subject matter. To address UX challenges, further studies should investigate which interactions are the most preferred as default, with advanced methods available through an options menu. Several participants also suggested more complex interactions, e.g., being able to use the virtual drill - a desire for greater agency.

4.6.6 WebXR, A-Frame, and Circles

Supporting all VR platforms presents many challenges, as can be understood from participant feedback on the UX, but WebXR provides an excellent foundation for multi-platform VR. However, the default controls of the laser-pointer for HMD, device orientation to rotate for tablet, and WASD keyboard and mouse to move and rotate can be challenging for unfamiliar users. Perhaps the laser controls used in A-Frame and Circles may not be usable. Exploring more direct manipulation methods, e.g., grasping [194], may be a more desirable option for some users. However, laser controls may be adequate for interactions out of reach and where the user can't physically grasp. To help improve selection accuracy, developers should consider using cone or cylinder-type interactions to help decrease user error when selecting smaller objects. Using orientation to rotate the virtual space is novel. However, in the case of tablets, it can create fatigue. Switching between a device orientation and another mode that doesn't require holding the device would be preferable. For desktop controls, using a mouse to select objects and rotate the viewpoint appeared to work well, as Circles uses selection-based targets to simplify movement.
4.6.7 Conducting a Remote Synchronous VR Study

Changing this study from a within-subjects design, with more closely controlled equipment and lab space, to a between-subjects design with a large variety of personal equipment was necessary and presented many challenges [184]. This online study was particularly difficult for users unfamiliar with the Oculus [Meta] Quest HMDs used in this study. Connecting the standalone HMDs to participants' smartphones presented issues, and the researcher had to help guide them. For the equipment lent out, we made a great effort to sanitize HMDs and tablets between participants and work with participants via video conferencing or distanced outdoor visits to troubleshoot. However, an advantage of the remote deployment was access to a broader network of participants online. We also took great care to partially automate the study so that a researcher need not be present. In this fashion, online VR studies could conceivably lead to vast and diverse participant pools. This is further enhanced by deploying experimental software via web hyperlinks rather than participants downloading an application.

4.6.8 Limitations

There were several limitations to this study. First, since this study was conducted remotely and with several personal devices, there is more significant variability in selection and search experiments [184]. For example, we could not control the participants' physical environments and personal device preferences configured. Nevertheless, that we arrived at results comparable to previous non-WebXR studies is a testament to the versatility of Fitts' law as a methodological tool. However, some further exploration into the higher TP scores is required. Additionally, though this study is likely a more accurate representation of how these devices would be used in a real-world case study, there is much room for improvement. For example, running a similar study within a more controlled environment, using more complex VLEs for the selection and search tasks to account for VLE distractions, landmarks, and natural occlusions, would likely be fruitful [107, 290, 291].
4.7 Conclusion

This three-part study explored the selection, search, and usability differences between three WebXR platforms – desktop, mobile (tablet), and HMD. We found that selection performance favoured desktop and tablet, whereas search performance favoured HMD and desktop. The selection results fell within reasonable ranges of past studies and in conjunction with themes captured, suggest that WebXR is a competent medium for learning, with some advantages in being easier to connect with learners using familiar web technologies. However, low usability for all three platforms due to UX ambiguity within the Circles framework UI, and VR platform limitations (weight, resolution), suggest that designing cross-platform VR is difficult. However, participants enjoyed the experience and were interested in further exploring VLEs and VLAs as shorter learning activities within their social learning spaces. This suggests potential in further exploring cross-platform WebXR technology such as Circles.

References

[Aggregated at the end of this thesis]
“... the similarity there is between the level on which characters, objects, portrayals and in a general way everything which makes up theatre’s virtual reality develops, and the purely assumed, dreamlike level on which alchemist signs are evolved.”

Artaud Antonín,
Chapter 5: Creation, Use, and Evaluation of Inclusive Virtual Reality Learning Experiences: A Case Study

This chapter has been published (or submitted) as a journal (or conference) paper:


5.1 Introduction

Increasing opportunities for experiential learning, i.e., “learning by doing” [180], in post-secondary education has become a focus in recent years [217, 389]. For example, while the Canadian post-secondary education (PSE) system has a high enrollment rate, it faces several challenges, such as low student engagement, high dropout rates, and employers dissatisfied with the graduates they hire [2, 59, 266, 416]. In response to these challenges, Canadian provincial authorities suggest that public funding increasingly depends on graduate employment, experiential learning, skills, and community impact, among other measures [267]. While questionable in terms of political intention, strengths of claims, and appropriateness of the criteria chosen [148, 280], these changes suggest a paradigm shift in education with a more concerted focus on increasing student engagement, community engagement, and more hands-on approaches through experiential learning.

Such a paradigm shift can move educational systems from simple knowledge transfer (transmissive learning) to a more efficient and engaging model based on experience and sensemaking (transactional learning) [233]. It can enhance the quality of graduates and their development of workplace skills – both technical and higher-order skills such as increased critical thinking, communication, and collaboration [53]. But the needs of modern society and challenges such as globalization, systemic discrimination, social justice, climate change, and democratization and management of emerging technologies require education to help transform students into thoughtful citizens capable of collaboration, critical reflection, perspective-taking, behaviour adjustment, and emotional engagement. This education model is called transformational or transformative learning [229]. Essential requirements of such a learning approach are inclusion to allow participation of a diverse group [40, 249] and deep engagement at both cognitive and
affective levels [115, 199], in addition to interactive, hands-on, and reflective features present in transactional/experiential models [179].

As a potential solution for more convenient and practical experiential and transformative learning opportunities, virtual reality (VR) can increase learner motivation [66, 165], increase embodiment [29, 165, 323, 400], improve both skill transfer [281, 401], enhance perspective-taking [140, 205, 322], improve the contextualization of learning [66], and allow for more effective collaborative learning [66, 382]. Unfortunately, it is still unclear, within its current “hype cycle” [206], what the use cases are for VR in PSE classrooms beyond technical skills-based training and virtual classrooms for remote participation [18, 50], where some are calling for user experience to shift towards empathy, critical reflection and perspective-taking, mindfulness, community experience, and lifelong learning [324]. Additionally, the creators of VR learning activities are often unaware of the communities in which VR will be used [78, 402]. Within this focus on building transformative and experiential learning [228] and the need to engage diverse groups of learners, we are critical of whether contemporary VR, despite all its affordances, is currently an inclusive medium for learning activities.

VR enjoys significant affordances such as immersion, presence, interaction, and visualization (Steffen et al., 2019). But, as with many other emerging technologies, the development of VR technology and applications suffers from a lack of inclusion as a primary design goal [67, 212, 243]. In this context, we define inclusion as the active participation of a diverse set of users with different gender, ages, ethnicity, social state, and physical and cognitive abilities [47]. The focus of contemporary VR is on head-mounted display (HMD) VR, commonly referred to as Immersive VR (IVR), with some VR learning endeavours additionally considering desktop or mobile VR [90, 196, 403], commonly referred to as non-immersive VR, though they can achieve some levels of immersion [203, 235]. Unfortunately, immersive HMD VR users may experience cybersickness [121, 244, 309], social anxiety from using unfamiliar technology around others [269, 298, 390], the inability to “grasp” virtual objects [245], and limited physical space to navigate virtual environments (VEs) [192, 311]. Users may also prefer using non-
HMD VR for specific perspectives and tasks, e.g., seeing others and notetaking [196, 403].

For VR learning activities to offer a more inclusive experience, some solutions explore multi-platform social VR that supports desktop, mobile, and HMD platforms [12, 116, 308]. The goal is to provide “platform scalability,” i.e., the ability to have an equivalent VR experience regardless of the platform used [309]. However, there has been limited contemporary research in this area, particularly in real-world case studies and on mobile platforms where the orientation of the display acts as a window [43] or “portal” [209] into a virtual environment (VE). A multi-platform approach to VR within social learning spaces, where users learn together and alone across continually shifting physical and virtual realities, using both physical and digital tools/artefacts to re-create more authentic, engaging, and transformational learning experiences [258, 309], appears significant. Particularly, in supporting VR to better support the experiential “expansion of consciousness through the transformation of basic worldview and specific capacities of the self” [85, 229].

Based on the above considerations and to increase inclusion as a central requirement of transformative learning, this paper focuses on how using multi-platform social VR for desktop, mobile, and HMD platforms performs in real-world learning scenarios. We feel that a VR framework that supports multiple immersive and non-immersive platforms is closer to realizing the principles of universal and inclusive designs for learning, where learners can choose various modalities to engage and express within learning [175, 325, 365]. Our research investigates the use of a multi-platform inclusive VR learning framework called Circles [308] and the associated design and development of several virtual learning environments (VLEs) and virtual learning artefacts (VLAs) for a gender diversity workshop that aims to highlight the challenges women face in the skilled trades as an example of a transformative VR learning activity.

Our specific research questions are:

1. What can we learn from the creation of VR VLEs and VLAs to guide future design and development for educators, developers, and researchers?
2. What are the challenges, opportunities, and surprises in using desktop, mobile, and HMD VR to increase inclusion in real-world VR learning activities?

3. What does an inclusive VR model look like that connects how people create inclusive and engaging VR learning activities with how people use them?

The gender diversity workshop is a context for our user study, not the subject of our research. Our research questions are related to using a multi-platform VR learning framework to increase learners’ inclusion and engagement, as we acknowledge the limitations in a single case study and several pilot studies evaluating how transformative learning has occurred [335]. However, we describe some themes suggesting some transformation occurring in Section 4. Our research and the qualitative analysis of participants' activities within three pilot studies and one workshop PSE gender diversity case study allowed the following contributions:

- Documentation of the iterative design and development of three VLEs and nine VLAs for a PSE gender diversity workshop.
- Novel insights on the process of creating VLEs and VLAs
- Novel insights on how people used the VLEs and VLAs in a multi-platform VR experience.
- A new model of inclusive VR use in learning includes engagement, inclusion, user and creator experience, and the individual and community.

Within this paper, we discuss how we researched, designed, and developed VLEs and VLAs within the Circles VR learning framework and how we used VLEs and VLAs within a remote-synchronous PSE workshop to help college faculty understand the challenges women face in the trades.

5.2 Design Process

Our design process followed an iterative design approach recommended by VR researchers, as "design must be iteratively created based off of continual redesign,
prototyping, and feedback from real users” [162]. Our initial research stage focused on collecting background and community information on what content we should create for the VR workshop content. After the “initial research” stage, we then performed an iterative design process whereby we developed VLE and VLA content, captured feedback on the content via pilot studies, analyzed the feedback, then modified existing content to create additional content and revise existing content (Figure 20). After several iterations, we had three VLEs and nine VLAs for our faculty workshop study.

Figure 20: Image of our iterative design process for creating virtual reality learning content.

5.2.1 Background - Gender Diversity in the Trades

Despite efforts to further equality and inclusiveness within STEM education institutions and professions, there is still a lack of female representation within STEM careers [242] and education [177]. For example, the skilled trades, where workers require “hands-on work and specialist knowledge … build and maintain infrastructure like our homes, schools, hospitals, roads, farms and parks” [328], are expecting a shortage in skilled trades workers [44]. More inclusive classrooms could help increase the number of trades workers graduating from trades training programs, where many graduates identify as male. Unfortunately, even within the classrooms themselves, women “are bombarded with subtle (and not so subtle) messages that signal they do not belong in STEM career tracks” [68], experience a lack of peer support and role models [177], and a lesser sense of belonging [381]. In response, some PSE institutions include diversity training into their curriculum to prepare trades students and faculty better to alleviate gender-based issues
by highlighting these challenges and suggesting solutions to avoid them [177, 242, 381]. Unfortunately, not all diversity training is effective. Engagement in diversity training workshops is low and, in some cases, may, paradoxically, increase discrimination [15, 49, 76].

5.2.2 Initial Research

In collaboration with a Canadian college, we studied whether introducing a VR learning activity into a faculty workshop highlighting women's challenges in the trades could better engage faculty to create positive behaviour changes [28, 140, 322]. We used Circles (Scavarelli et al., 2019), a multi-platform VR learning framework. Circles is web-based, supports three VR platforms (HMD, desktop, and mobile), uses selection-based interactions for greater inclusion, and offers a variety of development and management tools as an open-source framework we could customize as needed.

Before developing the VLEs, we decided to tie their creation to personal narratives, as prior research suggests more relatable and realistic storytelling helps people feel connected to the learning material [168, 296]. This approach also allowed us to design the proposed VLEs to focus on three moments (the past, present, and future) in a woman’s life, exploring a trades’ career path. We worked with the college’s journalism department to meet with and conduct several short informal interviews with a woman familiar with the college’s inclusion and diversity team who was willing to share her story about her trades career. These interviews captured several interesting themes regarding her struggles and successes, and the journalism team started thematically categorizing this material into several potential VLEs and VLAs. Unfortunately, just as we were wrapping up the information-gathering stage, the tradeswoman that volunteered her time could no longer participate, and we could not use her content for our VR experience. The reasons were unclear, but there was often a theme of anxiety about how her male colleagues and managers would react to her story if shared publicly. This experience illuminated how sensitive this content can be to the individuals participating. Fortunately, we had several videos of interviews with other women that shared their stories of past diversity in the trades endeavours that we could access and analyze to create themes that provided a basis
for designing the required VLEs and VLAs. These themes and proposed VLEs and VLAs were shared with the workshop coordinators, diversity specialists, and trades Professors to gauge whether the content suggested was authentic and respective to the subject matter. The journalism team’s themes and the associated VLEs and VLAs are described in Table 10.

Table 10: Themes identified within subject-area research, VLE question prompts and VLA description/narration text.

<table>
<thead>
<tr>
<th>Introductory Questions</th>
<th>VLA</th>
<th>Theme</th>
<th>Narration Audio and Caption (front)</th>
<th>Additional Description Text (back)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acceptance Letter</td>
<td>Excitement</td>
<td>“Despite their concerns about me getting this diploma in tech., I know it will open doors for me. My parents might not approve at first, but I'll show them it’s worth it.”</td>
<td>“The letter reads accepted and the anxious waiting has finally subsided. Now it’s simply down to getting approval from her family. Many of which still don’t understand the value of a college technician diploma.”</td>
</tr>
<tr>
<td>(1) How can we support women considering tech careers?</td>
<td>Parent’s Shop Keys</td>
<td>Confidence</td>
<td>“When I was young, the options my parents had were limited. They needed to work long hours for this shop, but I need to find my own path. Maybe my love of working with my hands and building could help automate areas in the shop.”</td>
<td>“The years of dedication and hardship her parents fought through are felt in those shop keys. She passes them daily, reassuring herself that is not her path. Yet her parents quickly formed a decision to follow their footsteps and continue the legacy.”</td>
</tr>
<tr>
<td></td>
<td>Math Homework</td>
<td>Frustration</td>
<td>“The idea of taking classes to become an accountant is not what I want. Sure, numbers come easily to me and I'm good at solving equations. But I'm also good at other things, being proficient in math doesn't define me.”</td>
<td>“Statistically administrative and financial roles tend to be more female accepting. Since Sarah has always excelled in math and helps with the taxes a program that's more 'feminine' such as accounting would suit her parents more.”</td>
</tr>
</tbody>
</table>
### VLE 2 – Classroom Electrical Lab (“In the Classroom”)

<table>
<thead>
<tr>
<th>Introductory Questions</th>
<th>VLA</th>
<th>Theme</th>
<th>Narration Audio and Caption (front)</th>
<th>Additional Description Text (back)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) How can we make our tech' classrooms more inclusive?</td>
<td>Drill</td>
<td>Group Dynamics</td>
<td>“Walking into the lab the first day was exhilarating and terrifying. I’m excited to learn and get comfortable with the tools. But, it's next to impossible when I'm always paired with someone who takes over. I was never exposed to these tools as a child growing up.”</td>
<td>“Men usually go into tech. with a better understanding of tools such as this drill. However, women may not have had the same exposure. Though with positive intentions men taking over exercises with unfamiliar tools prevents women from learning.”</td>
</tr>
<tr>
<td>(2) What are some strategies for dealing with unbalanced group issues?</td>
<td>Safety Gloves</td>
<td>Equality</td>
<td>“These glove sizes are almost impossible to work with. Yes, we need these for protection, but I also need to pick up fine objects such as wires and screws. If the school had a greater selection for all sizes, I'd spend less time adjusting and more time working in the lab.”</td>
<td>“To save on costs and space, schools tend to purchase generic sizes for safety and protective wear. Large sizes are common. Women often must compensate by adjusting or risking safety and fine motor skills by wearing ill-fitting attire.”</td>
</tr>
<tr>
<td></td>
<td>Instructor’s Clipboard</td>
<td>Exclusion</td>
<td>“Mr. Smith always seems more open to chatting about things with the guys, spending more time with their groups than ours. If he knew that I captained my basketball team in high school, maybe he'd ask me who my fantasy picks were?”</td>
<td>“As the professor walks around taking attendance, women notice he talks more with the men. Without knowing, the teacher is adding another layer of insecurity by assuming the women wouldn't have anything to interesting to talk about.”</td>
</tr>
</tbody>
</table>

### VLE 3 – Construction Worksite (“On the Job”)

<table>
<thead>
<tr>
<th>Introductory Questions</th>
<th>VLA</th>
<th>Theme</th>
<th>Narration Audio and Caption (front)</th>
<th>Additional Description Text (back)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(1) What can we do to make women feel Lunch Box Unwelcoming</td>
<td>After a long morning on the road, Jim and I are starving. When we get to the site, this sandwich is going to hit the spot. He mocks me</td>
<td>“Being excluded is not always obvious, but even something as simple as eating</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Question</td>
<td>Commonalities</td>
<td>Response</td>
<td></td>
<td></td>
</tr>
<tr>
<td>-------------------------------------------------------------------------</td>
<td>------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) What can we do when we see someone being excluded at work?</td>
<td>“I carry a picture with me at all times in my wallet, so that I can look at my family and remember why I keep pushing on through adversity. Sometimes, I just need a reminder before hitting a 10-hour shift with the guys.”</td>
<td>“With so many seemingly small challenges adding up to make going to work a chore, sometimes the additional motivation of being stubborn or supporting others can help. What about those that do not?”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Family Photo</td>
<td>“I need a stool or ladder to reach things, but I get this look from everyone like why is she even here if she needs that? But if the job is still getting done properly and efficiently, what does it matter if I need to reach things that most men don’t.”</td>
<td>“Job tasks remain identical regardless of size or gender. Handling large machinery can be a challenge, when less than average height. Creating added support or materials can help in accomplishing these tasks. However, for those who don’t require extras, it continues to isolate those who do.”</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stepping Ladder</td>
<td>“I carry a picture with me at all times in my wallet, so that I can look at my family and remember why I keep pushing on through adversity. Sometimes, I just need a reminder before hitting a 10-hour shift with the guys.”</td>
<td>“With so many seemingly small challenges adding up to make going to work a chore, sometimes the additional motivation of being stubborn or supporting others can help. What about those that do not?”</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

more welcome in tech' work? for eating healthy. Oh well, he only eats with the other guys anyway.” lunch together can create feelings of isolation in those that don't belong.”
5.2.3 Pilot Studies

Researchers conducted pilot studies during a college donor event (pilot study one), an educational conference (pilot study two), and as part of a formal visual and search
performance study (pilot three) [307]. Researchers set up all three VR platforms (desktop, tablet, and HMD) for the first two pilot studies at a table. They invited eventgoers to try the first created VLE (the electrician’s lab) and the three associated VLAs (Figure 21). Researchers did not guide volunteers in any way except to answer questions about the experience and help with equipment. In the third pilot study, as part of a between-subjects empirical study into the selection and search performance of different VR platforms, 45 users (18 female, 23 male, 3 non-binary, and 1 did not answer) between the ages of 18-44 ($M = 26.93$ years, $SD = 7.64$ years) with 15 participants assigned to each VR platform (desktop, tablet, and HMD) participated in an unguided exploration of the electrician’s lab VLE. Researchers performed the study remotely using videoconferencing, with only the researcher and participant present.

During the first two pilot studies, at the college donor and educational conference events, researchers found that participants were uncomfortable using unfamiliar (HMD VR) technology around others in a professional context, following prior research on individuals using emerging technology in public settings inducing social anxiety [41, 298]. Interestingly, using the more familiar desktop (laptop) version experience was not explored either. Perhaps, this is due to the lack of novelty or general discomfort of sitting down and trying the experience. In these settings, it was clear that participants preferred the tablet version of the experience. We note that tablet VR allowed participants to explore the VLEs and VLAs using a familiar semi-immersive device (as the device orientation adjusted their view of the virtual environment) and thus made it easier to communicate and connect with others while exploring the experience. These observations were interesting as it was evident that the social context of the gathering informed how comfortable participants were using various VR platforms. Participants were generally impressed with the visuals and novelty of VR and the subject matter (highlighting the challenges of women in the trades).

Researchers noted user experience (UX) challenges in developing a robust and flexible interaction system in 3D space in the third pilot. Participants criticized the UX's iconography as ambiguous and selection difficult on smaller targets. However, researchers also received positive feedback on the easy use of selection-based teleport and
VLA interactions. Participants also noted that the VLEs are excellent, with VLE ambient sounds, narrative audio, and visual textures registered as highly immersive. Also, contrary to researcher observations in the more public and informal social gatherings of the first two pilot studies, participants indicated that holding a tablet to tap on a screen to interact was heavy, awkward, and uncomfortable, tracking from previous research on using mid-air interactions for an extended time as being uncomfortable [143]. Participants criticized all VR platforms for several UX challenges, such as any text being “too hard to read close up,” the zoom button icon looking “like a search button,” and the “models intersecting with text,” making reading challenging in the VLEs.

Overall, participants preferred the more immersive HMD VR platform when the study was performed privately with a single researcher (the third pilot study) and chose tablet VR when used within social spaces (pilot studies one and two). Participants enjoyed the visuals, interactions, and subject matter throughout all pilot studies. However, participants were critical of the UX, noting how some aspects made things less immersive, e.g., the scale of a door, and wanting more immersive interactions, i.e., being able to use virtual hands to pick up objects rather than selecting objects with a virtual laser pointer. These participant observations highlight the challenges and opportunities around building VR learning activities that work across immersive and non-immersive VR platforms and varying personal preferences.

5.2.4 Development Process

We started our development by building a singular VLE representing the electrician’s lab to define our content-creation workflow. Then, we moved towards making the other two VLEs and related VLAs. Additionally, we had access to an electrician’s lab at the workshop’s college workshop to take several photos to help with texturing, i.e., we applied colours and images to a 3D model, making the lab creation more convenient. Our workflow followed the same general “iterative design” structure shown in Figure 20, where we repeated the process several times until we felt a complete version was met [162].
Development: With the development cycle, there are several steps to determining how to source, modify, or manually create 3D models, textures, and sound to create an immersive and “authentic” VLE.

- **Research:** Research our chosen themes and artefacts through web-based image searches and taking pictures of any artefacts or environments we can access, i.e., capturing photos of an existing electrician’s lab.

- **Design:** Sketch a rough layout of environments to start blocking out a scene with 3D primitives (i.e., cubes) within a 3D modelling software.

- **Re-use:** Search in 3D software sites for some open-licensed models on websites such as Sketchfab.com.

- **Create:** We model the 3D objects we cannot “re-use” using 3D modelling software, then texture using physically based rendering (PBR) materials that allow 3D objects realistically reflect and refract light across various lighting conditions [92]. We decided to work within the PBR workflow as the WebXR [386] framework that developers build Circles on, A-Frame [7], supports PBR as its default material system.

- **Sound:** During the iterative process, we also researched ambient sounds we can add to the environment, e.g., voices and exhaust fans in a lab. Circles uses the 3D spatial sound groundwork included in A-Frame. By placing these sounds at various places within the environment, users can hear the sounds realistically attenuating as they move through the space, significantly increasing immersion.

Peer Review: Once we have a rough VLE and VLAs, we test with the three VR platforms (desktop, mobile [tablet], and HMD) by asking peers inside and outside our development team to try the experience. This informal user evaluation helped us find scale errors, i.e., a doorknob larger than a virtual hand. It also allowed us to identify how the VLEs made users feel and whether users understood the VLE’s subject matter.
• **Pilot Study**: As described in more detail within Section 3.2, we were able to two social gatherings and one formal study to gather qualitative data on whether our development process was productive. These pilot studies were crucial for determining whether the VLE and VLAs were engaging and usable.

• **Feedback**: With the qualitative data captured from the pilot studies, we could analyze the data and act on any significant UX and understanding issues. This feedback helped find problems such as narrative audio and text not matching that we could fix for future iterations, that the sound found within the VLEs was well received, and that we should include more.

After thorough research, several pilot studies and general usability fixes with our VLE and VLA prototypes, we returned to our initial research, trades, and workshop communities for final feedback.

### 5.3 Case Study

Following our pilot studies and the development of VLE and VLAs, we performed the primary case study within the context of a gender diversity workshop. In this study, we recruited college trades faculty to participate in a workshop highlighting women's challenges in the trades. A teaching and learning specialist at the college acted as the workshop instructor, including traditional learning activities such as videos, discussions, and presentations in their teaching. We developed the VR learning activity described in this paper to increase workshop engagement and help participants internalize women's challenges in the trades by exploring authentic VLEs and VLAs via an inquiry-based teaching model [274] to enhance perspective-taking (van Loon et al., 2018), without the problematic embodiment, or “identity tourism,” of others [250]. This qualitative study used participant-observer notes [60] to analyze how participants engaged in a VR learning activity that used a multi-platform VR learning framework like Circles. We also captured data via pre- and post-experiment questionnaires.
5.3.1 Participants

We recruited 19 college faculty from a potential pool of 28 workshop participants who consented to have their data collected during this study. However, only 14 participants (7 female, 6 male, and 1 preferred to self-describe) between 18-74 years (the majority, 11 participants, in the 34-64 age range) filled out the pre-study questionnaire. Each participant chose which platform to use for this study to keep selection more natural and to keep participants motivated (10 chose desktop, 4 chose the HMD, Oculus Quest 1 [263] – though we note that one participant consented but did not fill out the pre-questionnaire used an iPad [156]). All participants had a “somewhat comfortable” knowledge of technology, and all participants but one were familiar with HMD VR, though only one had previously used an HMD VR device.

5.3.2 Apparatus

Though this study focused on the VR learning activity, we should note that it was just one part of the gender diversity workshop. The workshop instructor also used more traditional tools such as discussion, videos, and probing questions within the online course space to disseminate content. This workshop was remote-synchronous due to the COVID-19 pandemic, and workshop organizers used the Zoom videoconferencing tool [411] to connect with faculty participants. Regarding the VR learning activity, for the four HMD users, we lent out Oculus Quest HMDs. Each HMD device was sanitized, dropped off, and picked up at each participant's residence. Each HMD participant borrowed an HMD for approximately two weeks (at least one week before the study to have time to set up and troubleshoot any issues with the researcher). All desktop, and one tablet user, participants used their own devices. All “desktop” devices were Windows 10, using the Google Chrome browser [124]. Each Oculus Quest used the Chrome-based “Oculus Browser” [120] for VR performance and browser consistency. The researchers developed the VR experience using the Circles framework, described in Section 2.

We used SurveyMonkey [357] to collect consent and questionnaire data (pre- and post-experiment questionnaires). The pre-experiment questionnaire captured demographic information and a self-consciousness scale to detect social anxiety [313]. The post-
experiment questionnaire captured intrinsic motivation [153], self-consciousness [313], cognitive load [252], presence [374], and a system usability score [42]. For the "VLE and VLA Exploration," the participant is introduced to a website they log into using given credentials (so that no other users can interrupt the session), hosted on an EC2 T2-medium instance [13] of the web-based Circles framework. The Circles instance runs on a Node.js [257] web application using a MongoDB database [241], with Janus [161] networking running on an Ubuntu [372] cloud server.

Figure 22: The campfire – this VLE acts as a “hub” for connecting the three Circles’ “worlds” or VLEs used in the workshop via spherical “portal” hyperlinks that allow participants to click and travel to each respective VLE. Each portal hyperlink includes prompt questions below to encourage discussion and reflection on each of the VLE experiences. The campfire also acted as an informal meeting space for participants to connect to discuss via Circles’ voice chat the VLEs themselves or to engage naturally in off-topic conversations.

5.3.3 Procedure

There were two forms of workshops. One in which participants attended for two days, one week apart, and another where there was only one day participants were required to attend. The latter form was for participants that had participated in a similar workshop the previous summer and wanted a refresher. Workshop organizers structured the VR learning activity as an inquiry-based activity (IBL), “a process of discovering new causal relations, with the learner formulating hypotheses and testing them by conducting experiments and/or making observations” [274]. There are four IBL stages – orientation, conceptualization, investigation, conclusion, and discussion [274]. For the “orientation”
stage, to introduce the topic, workshop organizers first introduced the problems facing women in the trades with a presentation including what VLEs participants would encounter. For the “conceptualization” stage, to ask questions, workshop organizers pointed to the “introductory questions” (Table 10) posed by each of the three VLEs, within the campfire VLE (Figure 22). For the “investigation” step, the organizers encouraged individual and collaborative unguided exploration inside the VR learning activity. For the IBL “conclusion” and “discussion” steps, participants were encouraged to enter a “campfire” VLE where three “portals” exist they can click on to visit each of the three created VLEs (Figure 22). They could communicate and discuss what they found within this campfire with other participants. The workshop organizers encouraged reflection and pointed back to the “introductory questions” within the conceptualization stage to trigger the “disorienting dilemma” of transformative learning [54, 229], in which the organizers challenge participants to consider the perspective (van Loon et al., 2018) of the tradeswoman narrating the challenges she faces when selecting the VLAs. Each VLE also had a portal back to the campfire (Figure 21). After the VR experience, workshop organizers re-visited the questions introduced before the VR learning activity (Table 10). They asked participants to discuss and reflect on women's challenges in the trades, the VR experience, and how it connected to the workshop learning content. Some participants returned for a second day to present their experiences, conclusions, and potential transformation. Throughout the study, the researcher occasionally asks how they feel so that we can pause or stop the study if any participant feels any physical or psychological discomfort. Fortunately, all participants were able to complete the experiment with minimal issues.

5.4 Results and Analysis

We captured qualitative data from participants via two forms: (1) open-ended questions from the post-experiment questionnaire and (2) informal post-experiment interviews where we discussed the experiment with participants when picking up borrowed equipment approximately three to four days after the study concluded. Another data source was the participant-observer notes by the researcher who attended the workshop alongside the college trades faculty, following a memoing-style data collection [234].
Though the questionnaire data collected was inconclusive due to the limited number of participants, after compiling and transcribing all observation notes and open-ended questionnaire data into a digital database, we could highlight specific phrases and words to identify codes that emerged from the data [60]. For the deductive coding, we based our initial codes on a past literature review on the use of learning with VR in social learning spaces [309], as well as the findings of our pilot studies described in Section 5.3. We looked for codes based on identified concepts such as engagement and learning. For the inductive process, we followed an emergent coding approach [60]. We determined several themes during three rounds of identifying, merging, and sorting codes. Our research team then came together to discuss the chosen themes. We went back through the data until we felt that saturation, “a point in which no further insight can be gained through additional data analysis” [391], was met to determine the final themes (Table 11).

### 5.4.1 Themes Identified from Participants’ Data

In our analysis of participants’ data, we identified 28 codes grouped into 8 primary themes that best overview the significant aspects of using social multi-platform VR in a gender diversity workshop (Table 2). This analysis allowed us to explore the 8 primary themes and explore a more expansive theory of inclusive VR in our discussion section. Additionally, from these themes, we notice a pattern by which most themes fall under the umbrella of either “inclusion” or “engagement” (Figure 23).
Table 11: Starting with 11 deductive codes gleaned from prior literature and adding 18 more inductive codes found by repeatedly analyzing the qualitative data received, we settled upon 8 final themes after merging and sorting all codes collected.

<table>
<thead>
<tr>
<th>Deductive Codes</th>
<th># of Refs.</th>
<th>Inductive Codes</th>
<th># of Refs.</th>
<th>Inductive Codes (cont.)</th>
<th># of Refs. (cont)</th>
<th>Final Themes (after merging and sorting codes)</th>
</tr>
</thead>
<tbody>
<tr>
<td>UX Challenges</td>
<td>20</td>
<td>UX Positive</td>
<td>3</td>
<td>Remote Learning</td>
<td>1</td>
<td>Engaging Learning</td>
</tr>
<tr>
<td>Accessibility</td>
<td>0</td>
<td>VR Ecosystem Challenges</td>
<td>10</td>
<td>Social Challenges</td>
<td>8</td>
<td>Engaging VLEs</td>
</tr>
<tr>
<td>Authentic Learning</td>
<td>8</td>
<td>Artefact Storytelling Positive</td>
<td>1</td>
<td>Social Request</td>
<td>1</td>
<td>Engaging UX</td>
</tr>
<tr>
<td>Embodiment</td>
<td>0</td>
<td>Artefacts Engaging</td>
<td>10</td>
<td>Technical Challenges</td>
<td>2</td>
<td>Social Scalability</td>
</tr>
<tr>
<td>Engaging Learning</td>
<td>12</td>
<td>Hub VE Positive</td>
<td>2</td>
<td>Unguided Challenges</td>
<td>6</td>
<td>Platform Scalability</td>
</tr>
<tr>
<td>Inclusion</td>
<td>1</td>
<td>Increased Discussion</td>
<td>5</td>
<td>Unsure of Learning</td>
<td>7</td>
<td>Personalization</td>
</tr>
<tr>
<td>Presence</td>
<td>3</td>
<td>Indifference</td>
<td>7</td>
<td>VEs Positive</td>
<td>5</td>
<td>Skepticism</td>
</tr>
<tr>
<td>Remembered Learning</td>
<td>7</td>
<td>Multiple VEs Positive</td>
<td>2</td>
<td>Watercooler Effect</td>
<td>1</td>
<td>Internal and External Challenges</td>
</tr>
<tr>
<td>Social Scalability</td>
<td>4</td>
<td>Novelty Positive</td>
<td>10</td>
<td>Personal Preferences Requested</td>
<td>13</td>
<td>Transformative Learning</td>
</tr>
<tr>
<td>Platform Scalability</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Transformative Learning</td>
<td>10</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 23: Visualizing the hierarchy of the 8 themes discovered within our study within two primary factors of inclusion and engagement to create transformative learning. Rather than explicitly visualizing the themes as “Skepticism” and “Internal and External Challenges,” we leave them as overarching aspects to guide the future development of VR as learning tools.

**Transformative Learning**

The optimal goal of the use of VR in social learning spaces is for the transformation of our worldviews through increased critical thinking [75], better internalization of
knowledge with deep engagement at both cognitive and affective levels [115, 199], and inclusion to allow participation of a diverse group [40, 249]. It can be challenging to capture whether participants have transformed their worldview [335]. Still, within our case study, we can see some evidence for VR’s potential for “perspective-taking” (van Loon et al., 2018), whereby we aim to increase prosocial behaviour and empathy for others:

- “I liked the use of worlds to help establish a better understanding of the person featured in the VR setting. This helps to establish empathy.”
- “Yes, because I needed to give more attention to the situation. I feel I remember the VR component the best.”
- Some participants used the VR content in their discussions and final presentations, e.g., including screenshots within their presentation slides.
- The researchers note that some participants added more diverse examples in their teaching after the workshop and are now considering how to create more inclusive classrooms.

However, we note that it was not universal and that some participants also felt that the workshop did not help them better understand, as they “didn’t see the problem” and were disengaged from the beginning of the workshop. This may be due to technical difficulties, an inability to connect during a remote experience, or possibly even a disengagement around the subject matter (see Section 4.1.8 and 4.1.9 for more detail).

**Engaging Learning**

We found that learning with VR appealed to most faculty workshop participants, often coupled with enthusiasm for the possibility of using VR tools in their classrooms:

- “lots of potential with using VR here. I want to develop my own content, as it could be useful for international students that are expected to understand different construction protocols and techniques here in Canada.”
• “because I needed to give more of my attention to the situation. I feel I remember the VR component the best,”

• “I enjoyed Virtual Reality as I am a visual learner and can pick things up.”

Participants noted the novelty of using VR tools, but there was a good connection between the VR workshop materials and the lessons imparted by the organizer and VR content:

• “I found myself exiting re-entering rooms to recall specific message description phrases and words being applied in a specific room,”

• “The VR reminded me of things from the past (I have seen this).”

• “I can remember all of the rooms, most artefacts and the main point associated with them.”

The Circles’ virtual learning artefacts (VLAs), being the tangible knowledge foci of the learning content, where participants could select, manipulate, and read and hear content associated with each narrative, resonated well with most participants (“That was a very good, and interesting way of presenting the information,”). Many participants picked up and assembled around the VLAs. Some even wanted additional VLAs and decided it “was a good way to locate the information.” The participant feedback suggests that using knowledge-based VLAs to disseminate knowledge is promising, following past learning research around socio-cultural pedagogy [88, 185].

**Engaging VLEs**

Workshop participants connected with the Circles’ VLEs, noting that the VLEs helped with context (“it helped me contextualize the issues visual in a setting, compared to say - a training text on the issue.”). Some even commented on the possibility of creating empathy for the narrator associated with the artefacts ( “I liked the use of worlds to help establish a better understanding of the person featured in the VR setting.”), which was fascinating, as it was unprovoked and helped to showcase how the visuals, audio, and storytelling work together to create high engagement.
**Engaging UX**

Though not as strong a theme as “engaging learning” and “engaging VLEs,” some participants enjoyed being able to move around and interact with the space and artefacts, noting that “It worked for me” and it was “very intuitive.” The “internal and external challenges” theme highlights part of the UX significance, where the artefact interaction UX was the most problematic. All participants could use the system with some guidance, but many desired a more intuitive artefact interaction user interface (UI).

**Social Scalability**

As the Circles VR framework used for this workshop allows for multiple users to be in the same VLEs at a time, allowing individuals to see and communicate with each other’s avatars even when visiting other VLEs, there were observations on how the social aspect was both desired and surprising. Some participants enjoyed connecting in the remote faculty workshop and naturally and informally used the campfire hub to talk about their experiences in the workshop or even about off-topic conversations, creating a sort of virtual “watercooler effect.” This surprising water cooler effect suggested that having an always online space for learners to connect within more immersive VR experiences could be valuable for community building, particularly for remote learners. We also found that allowing participants to continue talking to each other, even while visiting other VLEs, helped to enhance the social connection [159, 334]:

- “I liked seeing other people and what rooms they were in. It made it feel more interactive.”

- “I liked being able to see other people because it gave more of a sense of interaction.”

Also of note is that the use of VR does appear to require social protocols to be more explicit, as not all users were familiar with how to share the space with others:

- “The social protocols we realize in a real setting I found unavailable and remained largely mute.”
• “It was a little uncomfortable as they weren't people I know in real life.”

This participant feedback suggests that in a remote and virtual setting, the anonymity granted by VR tools can still make people feel socially conscious of their interactions within the space. Additional social interactions could better connect individuals and better guide users into the social VR space should be a future consideration for using VR in social learning spaces.

**Platform Scalability**

As one of our deductive codes, platform scalability (supporting desktop, mobile, and HMD-based VR) was robust in several ways. Most chose to use desktop VR, as this was more comfortable and familiar, but a few did try HMD VR with great enthusiasm. However, switching to desktop VR from HMD VR was crucial because some had issues with their HMD, i.e., batteries running out, feeling uncomfortable, or even having trouble connecting the Oculus Quest HMD to their phones to set up. This flexibility of being able to switch between platforms during VR learning activities is essential to allow for “temporary” and “situational” scenarios described within Microsoft’s inclusive toolkit [325, 414] and follows from prior VR research, where students switch between VR platforms depending on the required tasks [403].

**Personalization**

The ability to have different and additional ways to navigate and interact within the VLEs was requested by many workshop participants:

• “Mouse movement backwards to what seems natural to me.”

• “The interactions were unnatural but necessary; when I could do more natural movements (e.g., turning my head), the experience was much better.”

Workshop participants also wanted more interactive and objective-based activities, including more VLAs to explore. VR users have different desires and needs, and including various controls and VR learning activities would be helpful in better engaging with more
participants. This feedback follows reasonably from the pilot studies, where participants using mobile devices found the device orientation to adjust their point-of-view natural and novel but ultimately wished they had a way to use their fingers after extended periods. Perhaps each user should be able to choose what types of interactions and navigation techniques are available to them at the beginning of the experience or change them during the experience via customizable menus, for example.

**Internal and External Challenges**

Many of the challenges the workshop participants faced were surrounding the ecosystem, where the standalone Quest VR HMD required a Facebook account and phone to set up the device, or there were technical difficulties and social challenges where some were unsure of how to interact with others. Additionally, there were UX challenges with the framework itself. Some participants felt the button iconography was unclear around VLA selection and manipulation and were uncomfortable with the VLAs occluding other objects within the VLE. Participants also text challenging to read in lower-resolution VR HMDs. Much of the feedback could be described as internal challenges related to how the individual understands how to use technology. Still, others were external, where challenges were created by others sharing the virtual space or technology challenges. Many of these challenges stem from a lack of personalization, unmet expectations, i.e., assuming buttons did one thing when they did another, social distractions, or technology-based or social-based anxiety.

**Skepticism**

As expected with most novel learning approaches, there was skepticism around using VR in social learning spaces. Some of this took the form of uncertainty about the new technology where some were not impressed with the technology ("while the activity is interesting, words could have yielded the same result.") Others were indifferent to the material itself, perhaps even disagreeing with the context of the workshop ("the artefacts had very little to do with the facts for me.") Other challenges surrounded the unguided approach to the VR learning activity, where participants wished for more straightforward
instructions and objectives on what they were to do within the Circles’ VLEs. The unguided challenges stem from the teaching method and suggest that using the same material in different ways, i.e., having both guided and unguided approaches, may help engage more learners.

5.5 Researcher Reflection and Discussion

This section will refer back to the first two of our three research questions. The third research question is discussed in Section 4.3.

**RQ1. What can we learn from the creation of VR VLEs and VLAs to guide future design and development for educators and researchers?**

We chose to create the VLEs and VLAs, and their associated visual, textual, and aural content within a rigorous research phase in conjunction with members of the learning community (the workshop instructor from the college’s teaching and learning services), the trades community (women in the trades), the inclusion and diversity community (the college’s diversity and inclusion specialists), and the storytelling community (journalism professors and students that helped take the research data into visual artefacts to tell an engaging story). The participatory or community-driven design process “based on a principle that the environment works better if the people affected by its changes are actively involved in its creation and management instead of being treated as passive consumers” [304] helped clearly define the VR learning content required. However, there were some challenges. Due to the sensitive nature of the subject matter, one of our interviewees had to drop out unexpectedly after several weeks of communication, fearing some work-related backlash from sharing her story. Part of this issue may also have been us not being clear about what the project would look like and with whom the project would be shared. Fortunately, the diversity and inclusion team had other interviews and prior research from other gender diversity in the trades initiatives that they were willing to share with the journalism team, which helped us create an engaging narrative around the VLEs and VLAs. Collaborating closely with several experts and community representatives made our chosen VLEs and VLAs more authentic and engaging.
One of the primary challenges in creating the content was technical. Examples include using the browser’s web inspector to debug errors, working with complex 3D authoring tools, and creating 3D assets that work for less powerful mobile platforms. Fortunately, the developers created better workflows to avoid complex geometry and high-resolution textures over time. However, building for three vastly different platforms was still challenging, as we had also to consider the user experience across all VR platforms. For example, we needed to ensure each VLA was visually attractive across varying display sizes.

Additionally, we noticed some usability issues where we had the narrative audio play when a VLA was selected, different from the more succinct textual description that also became viewable. The two conflicting sensory modalities created cognitive load challenges for users trying to read and listen simultaneously, as noted by past “redundancy” multimedia principles [218]. We eventually changed the text to match the audio for better usability and accessibility. We also added a rotation button for users to flip the description to reveal additional content on the backside. Overall, much of the experience was simplified using the Circles framework and its selection-based interactions to work across all VR platforms similarly (Scavarelli et al., 2023). However, further research is needed to facilitate content creation for instructors designing immersive multi-sensory VR experiences.

RQ2. What are the challenges, opportunities, and surprises in using desktop, mobile, and HMD VR to increase inclusion in real-world VR learning activities?

As this project started, it was clear that any content created for this experience needed to be engaging, and, most importantly, authentic, as diversity training is not always welcomed or effective [3, 76]. Our study demonstrated the ability of a multi-platform experience to increase engagement and inclusion. Engagement, is full of engaging VLEs, UX, and learning, and inclusion, in the form of multi-platform support, social support, and personalization, become stand-out categories as the most well-received aspects of using VR in social learning spaces. However, there is room for improvement, as noted in our themes of “internal and external challenges” and general “skepticism” around the use
of VR in learning. These “VR challenges” suggest that we must also consider the socio-cultural environments surrounding the use of VR tools in social learning spaces, as asking participants to be exposed to the “disorienting dilemmas” of transformative learning [335] to trigger a cognitive shift can be challenging, and perhaps a cognitive priming step to reduce anxiety could be beneficial [137].

Some researchers have started to discuss and consider a more inclusive VR experience [78]. However, the increasing focus on high-fidelity HMDs and more inaccessible features [377], rather than a more multi-modal approach to allowing VR to exist across several platforms, suggests much to do. In this study, we were surprised that many participants chose desktop VR, as the unfamiliar HMD VR experience was perhaps intimidating. And those that did use HMD VR had many challenges in completing the initial setup due to the ecosystem challenges of connecting a Facebook account and smartphone to the Oculus Quest HMDs. And even with the HMD setup complete, some switched to desktop VR during the workshop to better use other applications, e.g., taking notes or using the videoconferencing tools.

Additionally, the social aspect of VR within the context of learning with VR presents some exciting opportunities. Having reflection spaces, i.e., the campfire VLE, to support processing, discussion, and reflection also created a virtual “watercooler effect” whereby participants felt comfortable discussing unrelated topics. When considering other social VR research where users may use HMDs to “fall asleep together” [213], there appears to be a large field of study into how parallel virtual worlds can create new and exciting social connections [309] – perhaps ones that can also help within social learning spaces. Expanding inclusion to cover gender, age, and cultural biases, and also a consideration for community-level participation [402], is particularly important in this regard.

5.6 A More Holistic Approach

For our final research question, we are interested in how the higher-order themes of inclusion and engagement are interconnected with the people creating the VR learning activities and the people using them.
RQ3. What does an inclusive VR model look like, that connects how people create inclusive and engaging VR learning activities with how people use them?

We refer to the usability of creating VR content as user experience (UX) and the usability of designing and developing VR content as creator experience (CX). Following, we describe the three primary continuums of outcome, people, and activity that make up a more effective VR model (Figure 24):

- **Outcome** refers to the essential characteristics of the VR experience. Engagement and inclusion are the two most important outcomes of any VR learning experience, and they are interconnected as more inclusive experiences are required so that all learners can be engaged. Increased engagement is one of the most listed affordances of VR, but focusing on more inclusive VR is an important aspect that requires more study.

- **People** are the groups involved in the VR experience. There is a significant study on individuals and how different VR systems and learning activities engage them, often in the form of user studies. However, as noted by researchers [402], engaging with a community is more than the sum of individual engagements. A community, often described as people with a common goal, shared practices and traditions, and a sense of belonging [25], interacts with technology through different mechanisms [360]. In the People continuum, designers and developers consider individual and community levels when designing a VR experience.

- **Activity** refers to what actions people have. A robust UX framework is required for designing inclusive and engaging VR learning activities. However, we also need a powerful CX framework to make the design and development process inclusive and engaging.

Our proposed holistic model identifies significant areas of further research by defining three continuums and two levels for each. Our research offers early insights into these areas and encourages further research to address our limitations.
Figure 24: Simplifying the six points of our inclusion model to consider the three primary dimensions of the use of VR in social learning spaces, whereby we must consider the use and dissemination of the VR content and its creation. From the left, we have inclusion and engagement as a continuum that suggests that we need both – this was the conclusion drawn from our user data. On the right, we have a continuum where both creator experience (CX) and User Experience (UX) must be considered – a conclusion from our researcher observations. Finally, in the middle, we have a continuum where we must consider both community and the individual in all VR experiences in social learning spaces, a theoretical extension that results from our data and review of social learning spaces. Note that some aspects, e.g., inclusion, community, and creator experience are less investigated and require more study.

Limitations and Future Directions

Our insights and the proposed model are from a relatively small body of work, including the workshop study, several pilots, and literature reviews created within a quickly-moving landscape. More real-world case studies using multi-platform VR learning frameworks like Circles to explore how VR learning activities can be more engaging and inclusive are required to understand better the many interconnected aspects of creating a transformative VR learning activity. It would also be pertinent to explore more real-world case studies
[71] where the physical and social spaces are a more significant part of the exploration [309]. These further studies should involve more participants (group size, role, and diversity), subjects, and different contexts such as museums and classrooms.

Additionally, CX requires further investigation [38, 78, 243]. Our insights are based on our limited observations of the design, development, and use of gender diversity VLEs and VLAs. However, engaging more developers to use an inclusive VR learning framework can illuminate the CX aspect of our model and VR design.

Our study focused on general aspects of inclusion and engagement. As a tool for transformative learning, the success of our, or any other experience, should be evaluated using clear criteria [335]. In this case, they are learning objectives and transformational observations. Further studies are required to focus on these aspects, with a better understanding of how these learning dimensions influence one another.

5.7 Conclusion

We identified inclusion as a central requirement of social and transformative learning. We addressed the inclusion problem in VR-based social learning spaces by developing several VLEs and VLAs and studying users' and creators’ experiences in a multi-platform VR learning activity for a college’s gender diversity workshop. We gained novel insights by analyzing participants' data and our observations. These insights resulted in a new model for VR-based social learning spaces that consider the outcome, people, and activity involved in creating and using VR learning in social learning spaces. We believe six concepts emerged from this model that are essential in developing VR experiences in learning and possibly beyond. As such, our primary contribution is to draw attention to these concepts, identify the less investigated levels of each of the three continuums, and offer some initial insights and future work through our findings.

References

[Aggregated at the end of this thesis]
"Virtual worlds are not illusions or fictions, or at least they need not be. What happens in VR really happens. The objects we interact with in VR are real."

David J. Chalmers,
Chapter 6: Overall Conclusion

In this thesis, we described four research objectives of exploring VR in learning, starting with understanding the current state and potential of VR/AR technologies in learning (Chapter 2), then developing an inclusive VR learning framework for social learning spaces (Chapter 3), then evaluating the usability and performance of the VR learning framework (Chapter 4), and finally, exploring the use of the VR learning framework in a real-world case study (Chapter 5). This thesis and the several papers (Section 1.5) provide an alternative approach for how researchers, educators, and developers can design and use VR in learning frameworks with a socio-cultural foundation to be more inclusive and engaging. We describe how multi-platform social VR and WebXR can offer a strong starting point for creating more inclusive VR. We also describe an in-depth study into the performance differences between desktop, HMD, and the under-researched mobile VR platforms while suggesting some interesting future directions that indicate that VR platform choice changes for individuals depending on social situation and task. Additionally, within our real-world case study, we find that VR may be well suited for learning activities rather than a classroom replacement, with the potential as a transformative learning tool with fascinating social interaction possibilities. We feel that the totality of this work provides a substantial extension of existing learning in VR design strategies to create more inclusive and engaging VR learning experiences within social learning spaces. In such spaces, we must consider the interconnectedness of the learners with the physical and virtual environments around them, including other learners and the culture of their communities. Our primary contribution to this interconnected model includes the consideration of roles, more accessible interactions across varying virtual and physical spaces, the importance of both the creator and user experience, and the proposed multi-dimensional representation. Our real-world pilot and case studies and efforts by our research partners in using Circles within their research projects provide evidence that transformative learning is happening within this novel form of learning in VR. This section will expand upon our summary of the completed work while noting the limitations and future direction for this research.
6.1 Summary of Findings

Looking back on our research objectives (below), we can address the scope of what we observed during this thesis research.

**RO1. Understand** the state of the art in VR's educational potential, opportunities, and challenges.

Within Chapter 2, we explored the entire “extended reality” (XR) spectrum, focusing on the two main areas of research within learning, Augmented Reality (AR) and Virtual Reality (VR) - motivated by how closely related each form of XR is. Our conclusions on the potential of using VR/AR within social learning spaces centred around accessibility and limited inclusivity while acknowledging that VR/AR should not be a classroom replacement, and there are conflicting studies on the effectiveness of VR/AR for learning. Additionally, the pedagogical foundations of VR/AR are not well described, and more real-world case studies are required to understand these challenges. Specifically, in this overview, we describe three areas of accessibility that need focus in future VR/AR learning endeavours that consider the parallel realities (virtual and physical) of social learning spaces:

- **Platform Scalability**: supporting multiple VR platforms (desktop, mobile, and HMD) to encourage multiple means of user engagement and expression.

- **Social Scalability**: supporting a variable number of users together and alone, encouraging multi-user interactions via a messaging layer.

- **Reality Scalability**: Encouraging the design process to consider physical and virtual realities and their interconnectivity. E.g., how much physical space is available and whether the virtual space realizes the physical space.

**RO2. Develop** a VR framework using a socio-cultural pedagogical foundation.

We set out to create a practical and theoretical framework for making creating more engaging and inclusive VR learning activities more straightforward for researchers, educators, and developers. We developed the open-source Circles VR learning
framework, using WebXR to support multiple VR platforms, as an example of such a framework. We built Circles to provide a stronger foundation for more inclusive activities by including platform scalability, social scalability, and reality scalability design guidelines into its core features, such as selection-based interaction, support for multiple VR platforms (desktop, mobile, and HMD), networking components, and virtual learning artefacts. We derived many of these “scalability” design guidelines from socio-cultural learning theory and universal, social immersive, and reality-based design, whereby we must consider the individual learning tools and learning artefacts, environments, and the others we learn with as interconnected. Additionally, through several pilot studies, we determined that there are two additional scalability dimensions required, building from the first three described in the previous RO(1):

- **Interaction Scalability**: All interactions should encourage low physical effort single-selection interactions and the ability to scale to more advanced controls for more experienced VR users.

- **Information Scalability**: Encouraging design to use multiple sensory modalities and consider how we communicate information to and from each other. E.g., virtual learning artefacts have visual, textual, and aural properties, and we should allow personalization on how information is given and received (communication and avatar visibility).

**RO3. Evaluate the performance and usability of selection-based interactions and search across desktop, mobile, and HMD VR.**

Before adequately using the Circles framework in real-world case studies, we wish to understand better the performance and usability of the fundamental selection and search interactions. We also wanted to evaluate how usable it is for users to manipulate the viewport into a virtual environment to find interactive objects. We found that the performance of selection tasks via a formal Fitts’ law study was in line with previous non-WebXR studies, where desktop performed best, followed by tablet, then HMD. Search performance was more challenging than in past studies due to a lack of standards, but we found that HMD performed better than desktop and tablet. Overall, usability was good,
though some users criticized the ambiguous UI iconography. Still, overall, Circles was determined to have a strong foundation for supporting multiple VR platforms for learning.

**RO4. Explore the design and development of transformative social VR learning activities.**

With Circles designed, piloted, and developed, we needed to perform a real-world case study of its use within a social learning space. This case study also allowed us to explore how to design and develop VR learning content more thoroughly and evaluate its use within real-world scenarios. This study determined that Circles has excellent potential for making multi-platform social VR learning activities easier and that creating experiences across three different VR platforms (desktop, mobile, and HMD) is challenging. However, we observed increasing inclusivity and allowing users to switch between platforms that best suit their tasks and preferences was vital. We also found that the social features created some surprising and fascinating interactions, such as the virtual “watercooler effect” and learners seeing and connecting from different virtual learning environments. The most considerable usability challenges concern interacting with virtual learning artefacts and technical issues using HMDs. Additionally, we were able to describe our iterative design process with the communities involved in the project to design and development of virtual learning artefacts and virtual learning environments. Based on our results and observations, we proposed a new model for creating more transformative, inclusive, and engaging VR content.

**6.2 Lessons Learned**

During the several years of research into making VR learning activities more inclusive, we found this project's scope quite large, as trying to understand and develop a VR learning framework comprises many practical and theoretical considerations. E.g., understanding what VR is, how we use it learning, and then narrowing that down into something of smaller and significant scope by focusing on increasing inclusion via several “scalability” design principles. Even within this scope, we still needed a context for learning and looking towards VR’s most fascinating affordance of “perspective-taking,” embodiment, and new ways to collaborate. From these observations, we could discern that transformative learning would be a robust use case for VR technology. However,
even within this space, we still required much time to develop Circles before formally evaluating it. Fortunately, along the way, we were able to pilot the creation of experiences such as creating the Viola Desmond worlds for conferences, allowing us to connect with different communities, such as Viola Desmond’s sister, Wanda Robson, to make sure we could release the content through an open-source license. Additional communities of note were various academic and educational conference goers, WebXR developers, peers, and colleagues that allowed us to pilot-test, catch significant issues, and help motivate our direction. This motivation was immensely beneficial as the project appeared vast at times, mainly when we had to adapt to a COVID-19 pandemic to watch and teach our children from home and develop a new system for running remote studies. Ultimately, we feel that Circles and its associated studies and papers provide novel contributions to the learning, research, and VR developer communities. Even though we wish we could have run more studies and studied more aspects of using Circles within social learning spaces, there is a compelling framework and foundation for inspiring future research while continuing work on Circles with additional accessibility and social features.

6.3 Limitations and Future Directions

This research on creating a more inclusive and engaging VR framework resulted from the chaotic and accelerating changes in VR technology and culture due to the COVID-19 pandemic and the rising and falling of various VR ventures and excitement. In Chapter 4, we were challenged by the COVID-19 pandemic and the inability to use a formal lab setting to develop and use a completely remote testing apparatus for performance and usability testing. Performing similar studies within physical testing labs would reduce data noise and allow us to capture more observational data on how participants use multiple VR platforms in person and perform a within-subjects study to understand the individual differences between VR platforms more clearly. We also wish we could have spent more time on real-world case studies, including exploring connections with social learning spaces beyond conferences and classrooms such as museums. The workshop study described in Chapter 5 was a compelling and exciting look into multi-platform social VR. Still, its results are limited by our studies' relatively low number of participants and VR sessions. We want to run another similar study with more devices and participants.
to understand better how participants can use virtual reflection spaces for informal social connection (the “watercooler effect”) and how and why participants may choose different VR platforms depending on task, environment, and perhaps even emotional or physical state. From a user’s point-of-view, we built Circles to have features equally represented on each platform, but there may be cases in which this may be impossible or too limiting of each platform’s advantages. More studies, including longitudinal studies, into the use and development of Circles by other researchers, instructors, and developers would also provide more feedback on which features must be added or modified in response. Researchers, instructors, and developers require further study to determine what features to implement beyond the data collection, role-setting, and group-building components. Examples could include additional documentation and tools, such as allowing the use of familiar tools such as Unity [373], to help creators develop content that encourages the consideration of the five “guiding principles” described in Table 2, Section 3.2.3 in the initial design of VLEs and VLAs.

Additionally, more formally studying the transformative and social effects of the Circles VR learning framework would be beneficial as our observations were indirect. We wish to explore other research areas, e.g., how to make the Circles server easier to set up and connect with other servers, what other communication features we can add to increase communication and collaboration skills, how we should approach sharing social learning spaces with multiple VR platforms, how to make content creation more effortless, and how Circles features support or detract from non-transformative learning activities. In the future, in addition to the areas mentioned above of research, we hope to study further how Circles can be used to connect with physical spaces, e.g., a museum, and how to make social VR learning activity creation more accessible to VR designers and developers.

Expanding the Circles framework (and VR, in general) to be more inclusive and accessible is also a priority for future work. Circles’ selection-based interactions were motivated by principles of universal design where we wish to have a low-effort interaction that is adaptable to many input systems, and this should include more extreme input limitations such as the “sip-and-puff” where users may only have access to one digital
button [6]. Future real-world case studies across a variety of social learning spaces should also allow us to capture better how different users engage with our system across a variety of environmental conditions and what features we may need to add or modify to serve their requirements, such as better understanding the connection between identity and avatar customization [145, 250], increasing usability, and exploring how haptics can impact inclusion. Future work could also include using AI tools and additional data collection techniques to determine better if learning is happening. However, this will also require us to consider better privacy tools for ethical data collection [269]. As the Circles framework grows, we will need to create better tools to allow users to feel safer within their virtual learning environments, e.g., incorporating “personal space bubbles” [84], recommended by other researchers to increase online safety [63]. Research efforts into VR inclusion concerning gender, age, ability, ethnicity, and culture have started and need to expand to make VR a more inclusive medium.

6.4 Concluding Thoughts

The design, use, and evaluation of the VR learning framework Circles provide an exciting outlook into making social learning spaces more engaging and inclusive. This research allowed us to explore alternative socio-cultural pedagogy to understand the interconnected aspects of learning with virtual and physical activities, communities, tools and artefacts. After surveying the current learning landscape with VR, we designed and developed a multi-platform social VR framework called Circles to provide more engaging, inclusive, experiential, and community learning experiences within social learning spaces. We then evaluated Circles’ performance, usability, and design decisions, including those informed by the WebXR API and libraries interaction assumptions, to support multiple web-based VR platforms. The VR learning framework’s platforms perform similarly to past selection and search studies. However, its 3DUI design and usability across desktop, mobile, and HMD VR platforms will require additional iteration and user testing. After evaluating the performance and usability of Circles and modifying and adding some features to adapt to the user feedback, we used Circles in a real-world faculty workshop highlighting the challenges facing women in the trades. In this workshop case study, we documented our design and development process of VR learning
content and used the developed content as a learning activity within the faculty workshop. We found some challenges in using non-desktop VR platforms, but the ability for users to switch to other VR platforms was beneficial. We also observed fascinating social interactions, transformative learning, and the importance of working with communities to design and develop VR learning content.

The Circles framework provides a strong foundation for future research and development into how platform scalability, social scalability, interaction scalability, reality scalability, and information scalability help to create more inclusive and engaging VR learning activities, such as assisting participants to understand another's perspective in Chapter 5. This research also provides a practical tool for others to use for their learning and research projects, as showcased in Section 1.4.2. Circles is not just a tool available for other researchers, educators, and developers to use and expand upon but also a tangible position taken on the importance of making VR in learning, and VR in general, more accessible and inclusive in its use and development.

We are maturing into the information age where we can carry the world’s knowledge in our pockets, environments sense, and adjust to us. Soon, more accessible HMDs may augment our vision to see the virtual reality that already shadows us in digital lockstep, simultaneously traversing parallel dimensions (virtual and real), perhaps as a vision for the “metaverse” [19, 214], “which allows people to be virtually represented by avatars in a digital environment where they can connect, socialize, work and explore scenarios or 3D immersive spaces with others who are not physically present” [406]. Recent commercial and research initiatives towards AR/VR, such as Meta's renewed concept of the metaverse [146], are evidence of its potential and a sign of the need for better inclusion and engagement. The work on Circles provides insight into how learning could become part of such a future by supporting multiple platforms and connecting with unique social interactions that traverse numerous virtual worlds. We hope that as researchers, developers, and educators explore the VR/AR/XR space further, we make sure everyone is included in its design towards a more positive, powerful, and transforming future. A future full of visceral discussion, reflection, critical thinking, and explicit connections to the world and communities around us, both physically and virtually.
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**Appendix I: Glossary**

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
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<tbody>
<tr>
<td><strong>360 Video/Imagery</strong></td>
<td>A video or image whose frames are projected onto the inside of a sphere so that a viewer can look in any direction to view the content.</td>
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<tr>
<td><strong>Activity Theory</strong></td>
<td>A Soviet psychology framework describing the interconnected elements (person, community, mediating artefacts and tools, division of labour, roles, object) of a socio-cultural system of real-life activities.</td>
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<tr>
<td><strong>Affordance</strong></td>
<td>The relationship between the capabilities of a user and the physical or digital properties of something.</td>
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<tr>
<td><strong>ARCore</strong></td>
<td>A coding library, developed by Google, to allow developers for mobile Android devices to easily incorporate mobile screen AR.</td>
</tr>
<tr>
<td><strong>ARKit</strong></td>
<td>A coding library, developed by Apple, to allow developers for mobile iOS devices to easily incorporate mobile screen AR.</td>
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<tr>
<td><strong>Augmented Reality (AR)</strong></td>
<td>The blending of virtual objects/elements into the physical world.</td>
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<tr>
<td><strong>C21</strong></td>
<td>A Canadian organization that has described the skills necessary for 21st-century success.</td>
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<tr>
<td><strong>Collaborative Learning Environment (CLE)</strong></td>
<td>A learning environment in which closely-coupled interactions occur.</td>
</tr>
<tr>
<td><strong>Collaborative Virtual Environment (CVE)</strong></td>
<td>A virtual environment created for collaborative, closely coupled interactions.</td>
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<tr>
<td><strong>Constructivism</strong></td>
<td>Refers to a learning theory that describes that learning being constructed from experience.</td>
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<tr>
<td><strong>Course Management System (CMS)</strong></td>
<td>Refers to a digital system utilized by instructors to organize and deliver interactive content to students within a classroom (either face-to-face and/or online).</td>
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<td>Term</td>
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<tr>
<td><strong>Degrees of Freedom (DOF)</strong></td>
<td>Refers to each possible axis of movement, within computer interactions. E.g. 3DOF could be X, Y, Z axis translation whereas 6DOF could be X, Y, Z axis translation and X, Y, Z axis rotation.</td>
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<tr>
<td><strong>E-learning</strong></td>
<td>Learning via electronic, and often remote, technologies that eliminate the need to be in a physical classroom.</td>
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<tr>
<td><strong>Education Virtual Environment (EVE)</strong></td>
<td>A Virtual Environment created for an educational context.</td>
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<tr>
<td><strong>eXtended Reality (XR)</strong></td>
<td>Referring to a spectrum that includes VR, AR, and everything in between.</td>
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<tr>
<td><strong>Field of View (FOV)</strong></td>
<td>Refers to how wide (width and height) a virtual camera sees a corresponding virtual environment. This can also refer to the actual screen size and how much of our vision it covers in VR. A small FOV means less of the environment is seen, whereas a large FOV means much of the environment can be seen simultaneously. i.e. traditionally, human vision is 120 degrees.</td>
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<tr>
<td><strong>Haptic Feedback</strong></td>
<td>Refers to the physical feedback from virtual worlds. This often takes the form of controllers that vibrate when a virtual hand touches an object, but future incarnations may also simulate and prevent users from passing through virtual entities.</td>
</tr>
<tr>
<td><strong>Immersive Learning</strong></td>
<td>Placing individuals in an interactive learning environment, physically or virtually, to replicate possible scenarios or teach particular skills or techniques. Simulations, role play, and virtual learning environments can be considered immersive learning.</td>
</tr>
<tr>
<td><strong>Information Scalability</strong></td>
<td>Encouraging design to use multiple sensory modalities and consider how we communicate information to and from each other. E.g., virtual learning artefacts have visual, textual, and aural properties, and we should allow personalization on how information is given and received (communication and avatar visibility).</td>
</tr>
<tr>
<td><strong>Interaction Scalability</strong></td>
<td>All interactions should encourage low physical effort single-selection interactions and the ability to scale to more advanced controls for more experienced VR users.</td>
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<tr>
<td>Term</td>
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<tr>
<td>Inquiry-based Learning</td>
<td>A type of active learning that encourages curiosity, exploration and research, presentation, and reflection.</td>
</tr>
<tr>
<td>Learning Management System (LMS)</td>
<td>Refers to a system educational institutions utilize to organize all relevant learning content, often described as a super-set of a CMS.</td>
</tr>
<tr>
<td>Multi-User Virtual Environment (MUVE)</td>
<td>A general term used for a VE that allows multiple users to be in the same virtual space simultaneously (often, exclusively. Remote users logging in, each with their hardware).</td>
</tr>
<tr>
<td>Platform Scalability</td>
<td>supporting multiple VR platforms (desktop, mobile, and HMD) to encourage multiple means of user engagement and expression.</td>
</tr>
<tr>
<td>Projector</td>
<td>A type of monitor that projects an image out into the world so that its images can be seen on assorted physical surfaces such as walls, projector screens, or even buildings.</td>
</tr>
<tr>
<td>Reality Scalability</td>
<td>Encouraging the design process to consider physical and virtual realities and their interconnectivity. E.g., how much physical space is available and whether the virtual space realizes the physical space.</td>
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<tr>
<td>Selection-based Interactions</td>
<td>Interactions, such as selecting an object or teleporting through a virtual; space, that is based on a familiar single click/tap/trigger selection from multiple VR platforms to increase VR accessibility.</td>
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<tr>
<td>Social Scalability</td>
<td>supporting a variable number of users together and alone, encouraging multi-user interactions via a messaging layer.</td>
</tr>
<tr>
<td>Social Learning Space (SLS)</td>
<td>where users learn together and alone across continually shifting physical and virtual realities, using both physical and digital tools to re-create more authentic, engaging, and transformational learning experiences.</td>
</tr>
<tr>
<td>Stereoscopic display</td>
<td>Refers to a display that simultaneously provides two different perspectives to each eye to simulate depth.</td>
</tr>
<tr>
<td>Transition Interface</td>
<td>An interface that is not VR or AR but can switch between the two at will.</td>
</tr>
<tr>
<td>Transformative Learning</td>
<td>A type of learning that develops a powerful and deep perspective change within an individual.</td>
</tr>
<tr>
<td><strong>Virtual Environment (VE)</strong></td>
<td>An environment that is completely virtual, often in a 3-dimensional form for computer interactive users to explore.</td>
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<tr>
<td><strong>Virtual Learning Artefact (VLA)</strong></td>
<td>A virtual object that contains and presents knowledge that can be interacted with, and shared with others in a social learning space.</td>
</tr>
<tr>
<td><strong>Virtual Learning Environment (VLE)</strong></td>
<td>A VE (Virtual Environment) is specifically created to help with learning of some sort.</td>
</tr>
<tr>
<td><strong>Virtual Reality (VR)</strong></td>
<td>The complete immersion of an individual into an entirely virtual world.</td>
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Appendix IV: CHI 2017 Late-Breaking Work Poster

*VR Collide! Comparing Collision-Avoidance Methods Between Co-located Virtual Reality Users*

This poster overviews early work on preventing user collisions within shared physical spaces [312]. This research was motivated by the inability to do so easily with contemporary VR HMDs. This led to considerations about using this technology within social learning spaces, such as classrooms with limited space.
Appendix V: IEEEVR 2019 Late-Breaking Work Poster

Towards a Framework on Accessible and Social VR in Education

This poster overviews our initial framework design and some VLEs to highlight Canadian Civil Rights pioneer Desmond [308, 376]. We have evolved the framework since, but this represents the first step towards contemplating more inclusive VR learning in social learning spaces.