EVIDENCE-BASED DESIGN AND PEDAGOGICAL PRINCIPLES FOR OPTIMIZING THE EDUCATIONAL BENEFITS OF VIRTUAL REALITY LEARNING ENVIRONMENTS

by

ADURANGBA “VICTOR” OJE

(Under the Direction of Nathaniel Hunsu)

ABSTRACT

There has been an increasing interest in the educational applications of Virtual Reality (VR) technologies in the last decade. This growing interest is fueled by the fact that VR technologies are becoming increasingly better at rendering real-world experiences and environments in virtual space to support learning. In engineering education, VR can be utilized to support classroom and laboratory learning experiences. For example, students can experience and interact with abstract engineering concepts in three-dimensional virtual worlds in ways that they could not in the traditional engineering classroom or with engineering textbooks. Although VRs are growing in popularity, and some early adopters of educational technologies are already using them in various ways for classroom instruction, very little is known about how best to design and use them to facilitate learning in the most effective ways. Most notably, there is a dearth of VR studies that are grounded in empirically tested theoretical frameworks of learning in multimedia environments within the engineering education research literature. As such, there is a need for research studies that examine VR learning experiences. Studies that investigate the cognitive and affective factors that influence VR learning are also highly needed.

This dissertation seeks to address these existing gaps in the engineering education research literature by exploring the research literature to highlight the current state of theory-driven VR research generally, and in engineering education in particular. The dissertation comprises a systematic literature review (Study I), a scoping review of VR research in engineering education (Study II), and an empirical VR study (Study III). The systematic literature review analyzes 63 studies to identify design and pedagogy principles for enhancing multi-media learning, and their effects on learning in VR media. Study II explores the landscape of engineering VR research and identifies several gaps in current VR research studies in engineering education. The study advocates for theory-driven VR research within engineering education and makes recommendations for the future direction of VR learning research in engineering education. Study III investigates the effect of integrating generative learning principles into implementing VR learning in an engineering static course. The dissertation highlights the empirical, theoretical, and practical implications of its findings for the instructional design of effective VR content and for future VR research.

INDEX WORDS: Virtual Reality (VR), design principles, pedagogy, cognitive theories, multimedia learning, generative activities, engineering education

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A Dissertation Submitted to the Graduate Faculty of The University of Georgia in Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

ATHENS, GEORGIA

2022

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In loving remembrance of Funmi Oje. *Your prayers are now being answered*.

ACKNOWLEDGEMENTS

Words cannot explain how grateful I am to God for guiding me through this unforgettable experience. I am grateful for the Lord's Unchanging Hand, which has held me from the beginning of my program to the end. I am also grateful to Dr. Nathaniel Hunsu for his dissertation advice and thorough review of this work. Your late hours spent fine-tuning the dissertation studies will not be forgotten. I am grateful to Dr. Dominik May for his open office hours and guidance on the dissertation work. I would like to thank Drs. James Warnock, Kristen Bub, and Joachim Walther for their contributions and feedback in making my dissertation a success. I would like to acknowledge Dr. Logan Fiorella's reviews, which were helpful in refining the ideas of my systematic review study. Dr. Logan, your work has inspired me, and it has only led to the completion of this dissertation. I want to express my heartfelt gratitude to Dr. Savadatti for his collaborative efforts and for being so gracious in granting me access to participants in my empirical study. I would like to offer my heartfelt gratitude to Margaret Sapp. Your kindness will not be forgotten. This dissertation project would not have been feasible without my loving professor father's prayers, support, and encouragement. Dad, your spiritual and psychological support has accomplished this. I am grateful for the support of my siblings, Star and Funso Oje, and family members. Many thanks to my amazing friends for their encouragement and support throughout this experience – Damola, Samad, Femi, and a plethora of others. Your words of support have kept me going. And to so many others that I may not be able to mention because of space constraints, I could not have gotten this far without your help. Thank you very much!!!

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CHAPTER 1

INTRODUCTION AND OVERVIEW

Virtual reality (VR) technologies are simulated environments that can be explored and interacted with by using computer devices, such as immersive head-mounted displays (IVR or HMDs) or desktop computer simulations (desktop VR). As a result of advancements in computer graphics, image processing speed, and cost reductions, VR has become more affordable and accessible to users, which has led to a proliferation of VR devices in the consumer market. VRs are used in various applications, including video gaming, medicine, architecture, and construction. Because of this technology's perceived capabilities, educators are also adopting VR for laboratory and classroom instruction with the expectation that students will be able to experience educational contents in previously impossible ways. For example, engineering students can learn abstract concepts about forces by interacting with physical simulations of the forces in a VR environment. Students can take measurements, estimate attributes of a virtual boom lift (excavator), and interact with the excavator in ways not possible with traditional engineering-based instruction such as textbooks, videos, and lectures.

VR has the potential to revolutionize education by providing students with engaging educational experiences; however, the technology is still in its infancy, and several concerns have been raised regarding its use in education. Some educational theorists and empiricists have expressed concerns that unmeditated use of VR technology may result in learning distractions, impede sense-making, and impede positive learning outcomes (Parong & Mayer, 2018, Makransky et al., 2020). Design and educational use of VRs are frequently based on technological trends, designer intuition, and instincts than on research-based learning and motivational theories, or on empirically proven learner-centered design (and pedagogical) principles. Although VR designs include technological and aesthetic elements that increase arousal, they may also contribute to cognitive overload and reduce sense-making by diverting learners' attention away from their educational goals. Existing multi-media theories assert that poorly designed VR technologies can lead to suboptimal learning experiences and produce undesirable learning outcomes (Parong & Mayer, 2018).

Some critics have argued that the growing body of literature on the learning effects of VR lack theoretical grounding and empirical rigorous (Hamilton et al., 2021; Radianti et al., 2020). Particularly, the current body of VR research in engineering education contexts largely ignores the implications of evidence-based design and the theoretical principles in informing the phenomenon they investigate (di Lanzo et al., 2020). On the contrary, studies of VR learning in engineering have overly focused on perceptions of usability and other similar factors and few studies have attempted to connect their findings to evidence-based theories and pedagogical practices.

In light of this, empirical studies that draw on theory-based design and pedagogy principles for facilitating VR learning are urgently needed. Such studies have the potential to clarify how to design and support VR learning effectively. Studies that investigate these gaps could also identify effective ways of how to best implement VR in engineering classrooms. With this objective in mind, this dissertation reports three studies that examined: how theory informs instructional VR designs, instructional pedagogies for effective VR learning, and the effects of applying generative learning principles to support learning in a desktop VR environment of an engineering content. The dissertation addressed the following design, pedagogy, and learning-related research questions in this dissertation:

1. What design and pedagogical principles can be used to enhance learning in educational VR environments?
2. How can we implement generative activities (pedagogies) in engineering classrooms to maximize the learning benefits of using VR technology in the classroom?
3. How do theory-driven instructional design and pedagogies help students to learn from VR?

The dissertation explores these broad research questions using the following theoretical frameworks: c*ognitive learning theories* (design-centered frameworks) and *generative learning theories* (pedagogy-centered frameworks). The studies described in this dissertation were grounded on these theoretical frameworks because they are the most suitable frameworks for exploring the design and pedagogy of multimedia and VR media learning through the lenses of the human memory architecture and cognitive processing. I was especially interested in discovering how the theory-driven multi-media principles facilitate learning and student engagement in VR environments. However, there has been no systematic synthesis of relevant literature to determine how these principles have been used within the educational VR field. Study I describe a systematic review that examine how educational researchers have used design and pedagogical principles that can facilitate positive learning outcomes in VRs. Building on Study I, Study II explores the landscape and trends of VR research in engineering education to identify the strengths and limitations of VR research in studies in engineering. Study III compared the learning effects of a desktop VR learning context and a traditional medium of learning in engineering. The study further examined whether adding a generative activity into a desktop VR activity facilitates students' learning experiences in engineering. In summary, my dissertation research explored the use of evidence-based principles grounded in learning theories to facilitate the design and pedagogy and support learning in educational VRs.

The remaining chapters of this dissertation are structured as follows: Chapter II describes a systematic literature review and synthesis of empirical studies that examine design and pedagogical principles in VR. The review summarizes the findings of these studies to highlight the effects of multi-media learning theories and principles to support the design and pedagogy for effective learning in VR environment. The review described in Study I also identify factors that may moderate the effects of these principles on VR leaning. Furthermore, the study highlights implications of findings and made recommendations for educational VR design and research.

Chapter III describes a positional study that found that VR research in engineering is lacking theoretical support and argues for a shift toward theory-driven VR studies in engineering education. Furthermore, the chapter highlights design and pedagogical principles that could guide the design of educational VR for engineering contents. Lastly, the chapter proposes potential directions for future VR learning research in engineering education. Chapter IV describes study that uses a quasi-experimental research design to examine the application of an instructional pedagogy that promotes student learning experience in an engineering classroom VR context. Lastly, Chapter V concludes by discussing the theoretical, practical, and empirical implications of the findings of dissertation research studies.

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CHAPTER 2

STUDY I: A SYSTEMATIC REVIEW OF EVIDENCE-BASED DESIGN AND PEDAGOGICAL PRINCIPLES IN EDUCATIONAL VIRTUAL REALITY ENVIRONMENTS

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[1] Oje A.V., Hunsu N., Logan F. Submitted to Educational Research Review, November 8, 2022

2.1 Abstract

As Virtual Reality (VR) has become ubiquitous in education, researchers have drawn on multimedia and generative theories to advance research in VR. Empirical studies have been conducted to determine whether multimedia principles facilitate learning in VR. In our study, we sought to identify the current state of research on how these relevant evidence-based multimedia design and pedagogical principles are applied to facilitate effective VRs in education. We conducted a systematic review of the evidence pertaining to the learning effects of these principles. We identified 48 reports and 63 independent studies that examined the cognitive learning effects of design and pedagogical principles in educational VR environments. Among the reviewed studies, immersion was the most studied principle. We observed that pre-training had the largest effects for design principles. Additionally, we found medium-to-large effects for generative activities (e.g., summarizing) integrated in VR activities. We identified potential boundary conditions, or factors that may moderate the learning effects of these principles on learning. Finally, we highlighted knowledge gaps and offered suggestions and implications for research and practice.

2.2 Introduction

As a result of advances in computing graphical capabilities, Virtual Reality (VR) technologies have become more prominently used in entertainment and educational purposes. VRs are computer facilitated realities that render or translate real-life experiences (or physical realities) into virtual or simulated spatial reality. For uses in education, Virtual Reality Learning Environments (VRLEs) are designed to enable learners to interact with instructional contents and activities in virtual worlds that mimic real-life experiences. For example, a learner can perform a biochemical experiment in VR without handling any chemicals or being exposed to any of the risks that accompany similar interactions in a physical laboratory. Additionally, VR environments can depict realism that stimulates learners' visual, auditory, and tactile senses to support learning in VRLEs. A VRLE can enable students to interact with, and experience three-dimensional (3D) models of complex machineries, physical structures and buildings, and galactic elements without ever leaving the classroom. Furthermore, students can better conceptualize abstract concepts and non-visual information about electromagnetism, electrical waves, chemical reactions, molecular structures, and interact with internal biological tissues or organs in VRLEs. Without the affordances of VR, such experiences would rather have been expensive or impracticable to depict in the classroom.

VRs are categorized as immersive and non-immersive based on the kind of virtual experiences they afford. Immersive VRs require the use of head-mounted displays (HMDs) that provide users with a multi-modal and stereoscopic generated image. As a result of the stereoscopic display, the learner feels a sensation of being immersed in the simulated and virtual reality. On the other hand, users of non-immersive VRs (or desktop VRs) can view, hear, and interact with the virtual environment through a 2D desktop interface using a computer mouse and keyboard. While users do not get a similar sense of being totally immersed in the environment (as IVRs afford), they can experience and interact with the virtual contents better than if such contents were in abstractions.

As educators are increasingly adopting VR to facilitate classroom and laboratory instruction, there has been an increase in empirical studies that examine the design of instructional VRs and their effects on several cognitive and non-cognitive learning outcomes. For instance, Makransky and Petersen (2021) reported that more than 500 studies that investigated uses and educational affordances of VR have been published since 2015. This growing body of research are documenting empirical evidence of the affordances of VR to support different aspects of formal and informal educational experience, and across all educational levels.

2.2.1 Related Work

A number of systematic reviews of VR studies in K-16 educational contexts have been published in this and the last decade (Hew & Cheung, 2010; Merchant et al., 2014; Mikropoulos & Natsis, 2011). Hew and Cheung (2010) reviewed empirical research studies on the uses of virtual worlds in education and the main research topics that have been conducted within the reviewed studies. Mikropoulos and Natsis (2011) examined the technological characteristics, design features and theoretical approaches of VR that contributes to learning. Merchant et al. (2014) reviewed studies that investigated the types of desktop VRs and the effect of some instructional features used in VRs on learning outcomes. These early reviews highlight the fact that VRLEs can stimulate learning engagement and facilitate certain learning outcomes. However, these early reviews were mostly focused on the affordances of desktop VRs.

With immersive VR (IVR) becoming ubiquitous, it is unclear how the issues associated with desktop VR in these reviews relate to those that accompany learning with IVR (Luo et al., 2021). With more empirical studies that investigate learning in IVR being published recently, a number of reviews of IVR studies have been reported in recently (Freina & Ott, 2015; Jensen & Konradsen, 2018; Luo et al., 2021; Radianti et al., 2020). For example, Jensen and Konradsen (2018) conducted a systematic review of studies published between 2013 and 2017 that investigated the use of HMDs for learning and training. While they concluded that IVRs may be valuable for skill learning and acquisition, they also noted IVRs may be less effective than non-immersive VRs to enhance certain educational experiences and outcomes. In their review of 68 IVR studies, Checa and Bustillo (2020) found that just about thirty percent of the studies they reviewed found IVRs effective for improved learning and training. The authors concluded that the educational benefits of VRs are still unknown. In addition, their studies also showed the effect or lack effect of IVR on learning may be moderated by design and pedagogical factors that needs to be explored further.

Hence, these findings and conclusions calls for research that explores how to use evidence-based principles to facilitate the design of VRLE, and support pedagogy and learning in VRLEs. Given the recency of the VR research literature, researchers have drawn on the design and pedagogical principles, and the theoretical and methodological contributions of the traditional multi-media learning literature to advance studies of learning and pedagogy in VR media. For example, studies that focused on VR learning have employed principles of multimedia learning such as the redundancy (Adesope & Nesbit, 2012), modality (Ginns, 2005), segmentation (Rey et al., 2019), signaling (Schneider et al., 2018), and generative activity (Fiorella & Mayer, 2016) principles to examine the effects of design and pedagogical factors on learning in VRs. The evidence for the learning effects of these principle in the traditional multi-media learning literature is robust and well-grounded by the several systematic reviews and meta-analyses that have been reported over the years. Although VR is a kind of multi-media learning environment, the VR learning experience is uniquely different from that afforded by most traditional multi-media learning environment. Hence, the extent to which findings and conclusions about these principles of traditional multi-media learning that previously reported transfer to designing and supporting pedagogically effective VRLEs is not fully known.

2.2.2 Rationale for the current review

Despite the recency of VR learning research, there has been a growing number of empirical studies that examined the application of traditional multi-media learning design and pedagogy principles in educational VR contexts. However, to the best of our knowledge, no study has endeavored to synthesize this growing literature to identify the current state of research on how these evidence-based traditional multi-media learning principles are applied in designing VRs that are effective for learning. We argue that such a review could synthesize and clarify the current state of evidence for the effects of these principles on learning in VR contexts, identify factors that moderate the effects of these principles on VR learning across the literature. Lastly, such a review could also identify knowledge gaps in the design and pedagogies of VR that are effective for facilitating learning.

In light of this, this systematic review will explore and synthesize empirical studies in the VR learning literature to identify which design and pedagogical principles of multimedia learning were examined in previous VR studies and summarize the general findings of these studies about the effects of these evidence-based principles to enhance cognitive processing that ensure learning effectiveness in VR. The review will also highlight gaps and the literature and suggests paths for future studies. The systematic review will endeavor to address the following research questions:

1. What research-based design and pedagogical principles of multi-media learning have been examined in VRLE?
2. What are the demographics, contextual and methodological characteristics of these studies?
3. What learning outcomes are examined by VRLE studies that implemented these design-based principles?
4. In what ways do these design principles affect cognitive learning outcomes?
5. What are the potential factors that can influence the design and pedagogical principles of VRLE?

2.3 Theoretical Background

2.3.1 Cognitive Load and Multimedia Learning

2.3.1.1 Cognitive Load Theory

The Cognitive Load Theory (CLT) is a design-focused theoretical framework that highlights the amount of information that the human memory architecture – working memory and long-term memory – can handle at any given time (Sweller, 2020). The theory assumes that new information is first processed in the working memory before they are integrated into existing prior knowledge and stored in long-term memory. Proponents of the CLT argue that the human working memory can only process a limited amount of information at any given time (Kirschner, 2002; Sweller et al., 2019). On the other hand, they posit that the human long-term memory, can store an infinite amount of information. Similarly, humans' memory system can recognize patterns and situations in order to acquire domain-specific expertise. For example, an expert can recognize thousands of chess board configurations due to the robustness of the schemas they have developed over time and stored in their long-term memory. Because the working memory has a limited capacity, it can become overloaded – especially when too many novel information needs to be processed information in a short time frame (Paas & van Merriënboer, 2020). Hence, the goal of effective instructional design is to minimize unnecessary mental loads – thus freeing up working memory resources and optimizing cognitive processing that engender learning.

Theorists describe three types of cognitive loads (extraneous, intrinsic, and germane) based on the cognitive processing they engender in the working memory (Sweller, 2005). Intrinsic cognitive load is the memory load caused by the inherent complexity of the learning material or task. Hence, intrinsic load depends on the inherent nature of (or the number of interacting elements in) the instructional material. The interactivity of elements in instructional material increases with the difficulty level of the material, or with the increasing complexity of the learning environment. Extraneous cognitive load is caused by suboptimal presentation or organization of instructional material or environment (de Jong, 2010; Sweller, 2011). Hence, extraneous cognitive load can be reduced by implementing efficient instructional design procedures. Germane cognitive load describes the mental load imposed on working memory by the activities that are required to automate new schemas in long-term memory. Put differently, it is the load that is required to deal with intrinsic load due to the learning material (Sweller et al., 2019). According to the CLT, instructional content design must incorporate instructional features that minimize cognitive overload due to extraneous loads, manage the complexity of intrinsic loads, and promote activities that can elicit germane processing.

2.3.1.2 Cognitive Theory of Multimedia Learning

The Cognitive Theory of Multimedia Learning (CTML) framework was proposed by Richard Mayer to explain the learning process and predict how learning occurs in multimedia learning environments. The CTML framework proposes that: (1) information is processed in working memory through separate visual and audio channels; (2) working memory processing capacity is limited; and (3) meaningful learning occurs as the learner chooses and organizes relevant details from instructional materials into coherent visual and verbal mental models and integrates them with relevant prior knowledge (Mayer & Moreno, 2003). Incoming multimedia information (e.g., texts, images, and audio narrations) are first picked up by the sensory memory and are transferred to the working memory, where they are processed to formulate a coherent mental representation of the message the material conveys. After they are processed in working memory, the new knowledge is integrated or accommodated into existing prior knowledge in long-term memory, where they are stored permanently. Drawing on the knowledge construction perspectives of the CTML framework, theorists anticipate that the design of multi-media learning contents and environments must take into consideration that: (i) the human sensory and working memory capacity is limited and (ii) suboptimal organization of multimedia content or information can cause a cognitive overload. Therefore, to be efficacious for learning, the design of multi-media contents or environments must carefully balance the sensory information that enters the working memory to reduce the likelihood of overloading the processing channels (Mayer, 2012). Similarly, learners must actively select the most relevant information from the multimedia content, organize the selected information to form a coherent mental model. And integrate the mental models so formed into already existing prior knowledge in long-term memory.

Building on the tenets of the CLT, the CTML theorists categorized cognitive processing of multi-media contents that occurs in working memory into three: extraneous, essential, and germane processing. Extraneous processing is the cognitive processing that occur when irrelevant material or distractions that do not serve any instructional objective are encountered. It is typically induced by incoherent or confusing material, or poorly designed learning environments (Mayer & Fiorella, 2014). As such, extraneous processing overload occurs when working memory resources are exceeded due to extraneous learning material or incoherent learning environment. Essential processing describes the cognitive processing of material that is relevant to the instructional objective and learning. Essential processing occurs in working memory as learners select and organize multimedia information to form coherent mental models. The cognitive demands of essential processing may cause intrinsic cognitive overload depending on the complexity, and novelty of the learning material (Mayer & Fiorella, 2021). Generative processing refers to the cognitive activities that are associated with generating meaning and making sense of the learning material (Moreno & Mayer, 2007). Generative processing is often stimulated by learning motivation and the efforts expended at constructing meaning and in understanding an instructional material.

Based on the main assumptions of the CTML framework, several principles for designing multi-media learning content that aims at minimizing cognitive overload and engendering germane processing have been deduced and tested empirically (Mayer, 2014). For example, the coherence, spatial and temporal contiguity, signaling, and redundancy principles have been proposed and tested for reducing extraneous processing (Mayer & Fiorella, 2014), while segmenting, pre-training, and modality principles are suggested for managing essential processing (Mayer & Pilegard, 2014). Multi-media learning principles that are proposed to promote generative processing include personalization and imaging (Mayer, 2014), immersion, summarizing, embodiment (Mayer, 2020), feedback (Johnson & Priest, 2014), and self-explanation (Wylie & Chi, 2014) principles.

2.3.2 Generative Learning Theory

The Generative Learning Theory (GLT) posits that learners generate meaning from instructional activities if they actively engage in re-organizing and integrating new information from learning material into their existing knowledge (Fiorella & Mayer, 2015; Wittrock, 1974). At the core of the theory is the selection, organization, and integration (SOI) model of generative learning. The SOI model suggests that meaningful learning occurs when learners select the most important components of the learning material. Strategic or engaged learners select important information when they pay attention to the most relevant written or auditory words, or static or dynamic graphics. Next, engaged learners organize (e.g., through hierarchical structuring) the material they had thoughtfully chosen to create meaning. Finally, they extract these ordered concepts or patterns and apply them to their prior knowledge.

Meaningful learning occurs when learners are motivated to understand the various aspects of an instructional material and actively participate in relevant learning activities. The SOI model acknowledges the importance of effort or motivation in generative learning by emphasizing the intentionality of engaged learners in the learning process (Fiorella & Mayer, 2015; Fiorella & Mayer, 2016). Several studies have indicated that generative learning strategies foster meaningful learning engagement. Some of these studies have examined the applications of generative strategies for facilitating learning in multimedia learning contexts such as game based (Fiorella et al., 2019), augmented reality (Buchner, 2022), and VRLEs.

2.4 Method

This review adheres to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines for systematic review (Moher et al., 2009). A systematic literature review uses systematic procedures to find, collect, critically evaluate, and synthesize studies to provide an overview of existing research (Gough & Richardson, 2018; Khan et al., 2003). We discuss our information sources, search method, eligibility criteria, data collection, extraction, and synthesis procedures in the following subsections.

2.4.1 Search Strategies

We conducted a comprehensive search of seven databases: ERIC, Google Scholar, EBSCOhost, Web of Science, and Computer Source to identify potential studies for our review. The search phrases included "virtual reality" OR "VR" OR "virtual learn*" OR "virtual world" AND ""educat*" OR "learn*" OR "instruct*" AND "multimedia" OR "multimod*". Because this review targeted studies reported in peer-reviewed articles, studies reported in dissertation, book chapters, or non-empirical articles were excluded. In addition, we performed forward and backward citation searches (snowballing approaches) and database alerts to monitor new studies to ensure our review captures the most recently published studies in our area of interest. The literature search was limited to studies published in the English language alone. Non-empirical studies such as existing reviews, meta-analyses and book chapters were excluded. The literature search was conducted between March 2020 and March 2022. Studies were included for coding if they satisfied the inclusion and exclusion criteria described in Table 2.1.

2.4.2 Study Selection process

The initial database search returned 1279 articles from all search indexes. A three-stage process that included the removal of duplicate articles, screening of abstracts and titles, and full text evaluation was used for study selection. The search index data was downloaded into EndNote® and subsequently exported as Excel files to manage the article selection decisions. Next, duplicate articles were detected and removed from the list. The titles and abstracts of articles that remained after duplicates were removed to determine whether each article satisfied our eligibility and criteria for study inclusion. Articles that did not meet the inclusion criteria were removed (Table 2.1). The full texts of the remaining 291 articles were examined to confirm that they met the study objectives and addressed the research questions. Consequently, 242 articles that failed to meet our selection criteria were excluded. The remaining 48 articles that satisfied our study selection criteria were retained for coding and analysis. A number of articles reported more than one experimental study. As a result, a total of 63 independent studies were coded for further synthesis.

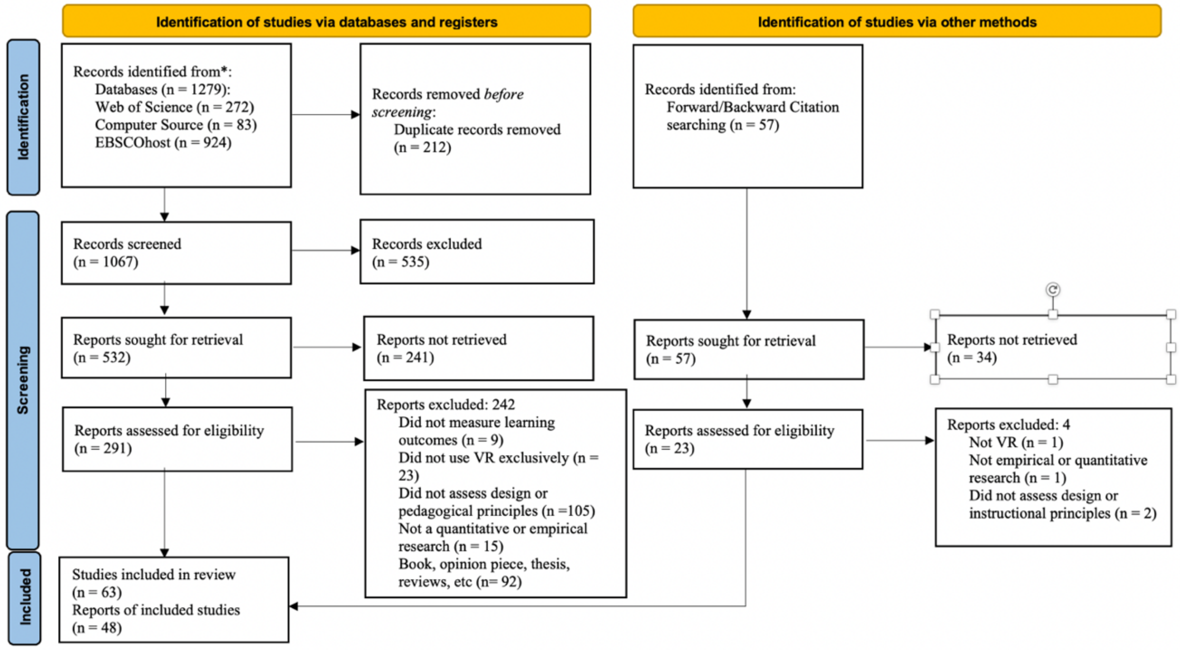

Figure 2.1: PRISMA, 2020 flow diagram (Page et al., 2021)

2.5 Data coding, synthesis, and analysis

A coding classification scheme for selected articles was determined based on our research objectives. As such descriptive, contextual, methodological, and evidential features of selected articles were coded. Descriptive features included study demographic information such as publication year, country, journal outlet, and keywords used by the articles. The evidence-based design, instructional and pedagogical principles that were the basis of each study were extracted based on existing theoretical frameworks of multimedia and generative learning. Additional principles that had not been previously categorized in multimedia and generative learning literature but were identified as being relevant to the design and pedagogies of VR learning among the studied selected were also coded. The extracted principles were categorized depending on whether they were intended to reduce extraneous processing, manage essential processing, or foster generative processing.

Studies were coded based on whether they had used experimental or quasi-experimental designs, whether they were conducted in lab-based or classroom settings. The types of VR used in each study (i.e., head mounted displays (HMD) or non-HMD VR) and how students interacted with learning activity in each VR study was coded. Also, research methods information such as study duration, study materials, measurement, participants educational levels, and the knowledge domains in which each study was conducted were also coded – unreported study features were coded as NR in the coding sheet. Lastly, we identified and coded for the major findings of each study to help us synthesize the learning effect of these principles. The Cochrane effect size calculator (Wilson, 2017) was used to estimate the effect sizes of differences between the intervention and non-intervention comparisons among the studies coded.

To facilitate quality control and inter-rater reliability, the coding process was iterative, and conducted in multiple stages. Two coders independently evaluated the articles retrieved to ensure that all relevant studies were included for coding. A random number of articles were chosen for a second round of inter-rater screening. After deciding on the coding scheme, the first author coded all the studies. During the coding procedure, the first author additionally identified and characterized categories that emerged. The first author, and four volunteered coders randomly selected and re-coded 16 of the articles after a training exercise. Minor differences in the coding were identified and handled through repeated discussions until all the raters reached a consensus.

2.6 Findings and Discussion

2.6.1 Research Question 1: What research-based design and pedagogical principles of multi-media learning have been examined in VRLE?

To recap, Mayer and colleagues proposed that three kinds of cognitive processing (extraneous, essential, and generative processing) occur during multi-media learning (Mayer, 2020). The working memory is overloaded when the cognitive loads that each of these cognitive processing impose on working memory is not properly balanced. This balance can be achieved by drawing on design and pedagogy principles that are essential to managing cognitive loads and minimizing cognitive overload. Twenty-one of the VR studies we coded and analyzed examined design principles for reducing extraneous processing, 9 studies examined design principles for managing essential processing, while 33 studies examined pedagogical principles of generative processing for fostering learning VR. The dimensions of the boxes in the tree map (Figure 2.2) illustrate the number of studies that focused on each principle. More studies examined the effect of signaling and scaffolding ($N = 8$ studies) for reducing extraneous processing and fostering learning among the VR studies analyzed. Modality effect on learning was the most examined ($N = 4$ studies) principle in the essential processing category, and effect of immersion on learning in VR was the most studied ($N = 16$ studies) in the generative processing category. The effects of segmenting, enactment, imaging, navigating, planning, and sequencing principles on learning were each only reported in single studies. As such, more studies that examine the effects of these principles on VR learning in different contexts are needed in the future.

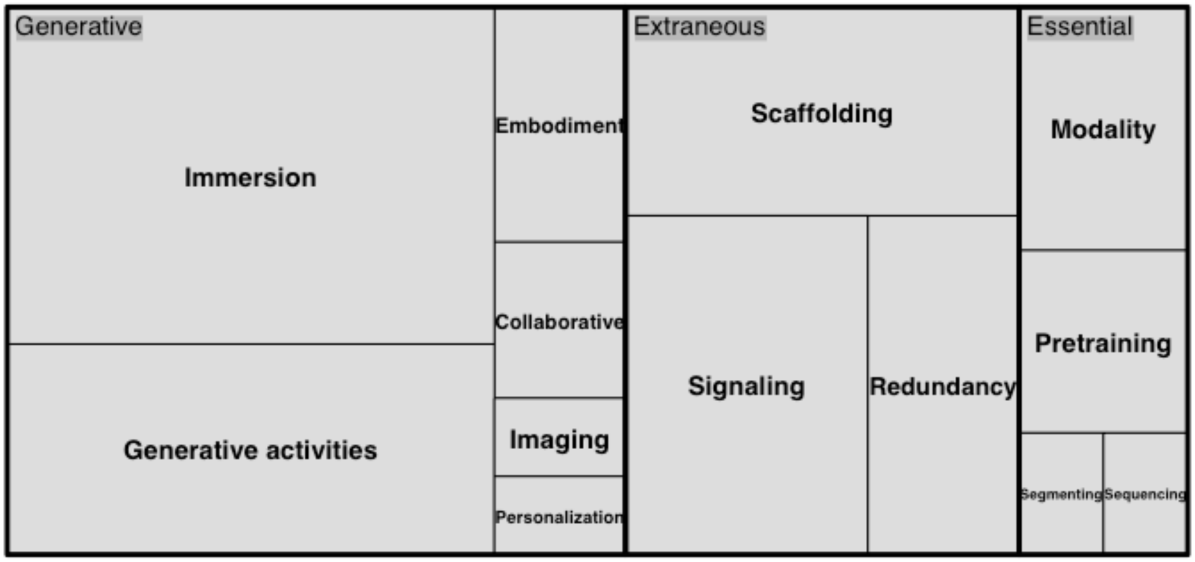

Figure 2.2: Tree map hierarchy classification of articles by principle and processing type.
*Source. Developed using R

2.6.2 Research Question 2: What are the demographics, contextual and methodological characteristics of these studies?

Demographics characteristics: Figure 2.3 shows an increasing count of published articles that examine the design and implementation of educational VR. Only one study was reported between 2007 to 2012. However, there have been a significant spike in VR research published in peer-reviewed outlets since 2018. A similar trend about for VR studies in K-12 research has also been observed (Hamilton et al., 2021; Makransky & Petersen, 2021), and in multimedia learning research in general (Çeken & Taşkın, 2022; Li et al., 2019).

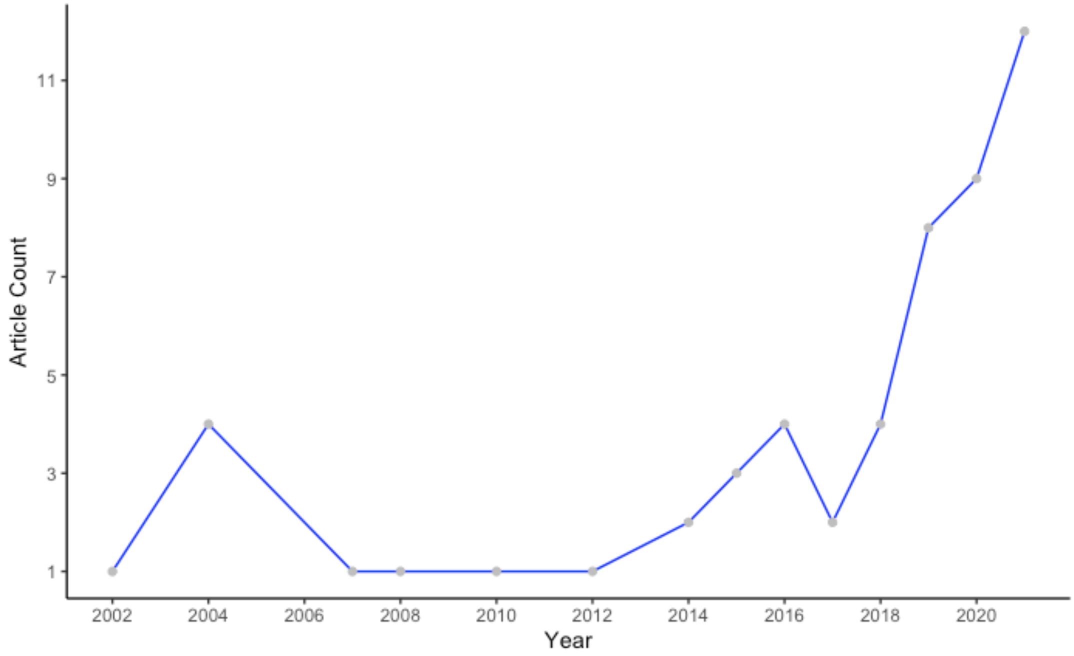

Figure 2.3: Distribution of instructional and pedagogical design studies in VR by year
*Source: Developed using R

A word cloud was created using R studio to highlight the most frequently used keywords among the VR articles coded (Figure 2.4). In order of frequency, the five most commonly used terms by the studies coded are as follows: virtual (30), learning (27), reality (17), multimedia (12), and cognitive (10). A few authors used keywords that are associated with generative learning. Most peer-reviewed VR research reports were published in Journal of Educational Psychology (*n* = 5), British Journal of Educational Technology (*n* = 4), Computers & Education (*n* = 4), Educational Tech Research Development (*n* = 4), Journal of Computer Assisted Learning (*n* = 4), and Computers in Human Behavior (*n* = 3). Table 2.2 shows that the studies were largely carried out in Europe (*n* = 18). Most of the studies included in this review were conducted in the United States (*n* = 15) and Denmark (*n* = 10). Because VR is becoming ubiquitous, more VR studies that investigate how design and pedagogical principles can be integrated to make them more effective educational tools using participants from other nations are needed. Such studies could clarify the generalizability of the learning of these principle across national and cultural backgrounds. Such studies could also provide data for future meta-analytic review of effects cultural difference on learning effects of these principle in VR environment (Mayer, 2017).

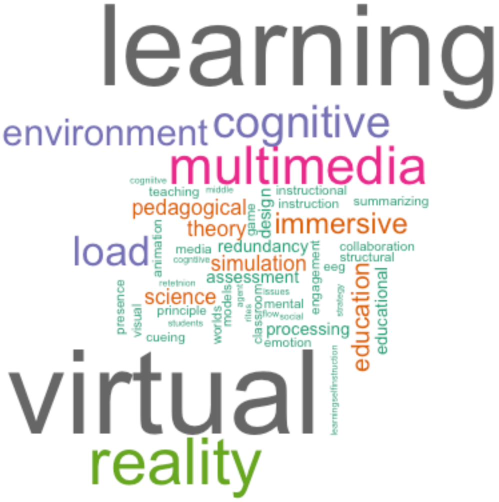

Figure 2.4: Word cloud showing article keywords
*Source: Developed by author on R

Contextual characteristics: Participants distribution across the study examined ranged between 32 and 287 (*M* = 97.35, *SD* = 52.22). Twenty-nine studies involved university or college student participants – some prior reviews have also noted that most VR-focused research have been conducted among college student (Alemdag & Cagiltay, 2018; Hwang & Tsai, 2011; Wu et al., 2020). Thirteen studies involved high and middle school students, while 2 studies involved samples drawn from the general population (Figure 2.5). Relatively fewer studies had examined the learning effects of VR with younger student populations. Without more K-12 VR studies, we may be less informed about how younger students interact with learning in VR environments. As such, future studies should explore effective pedagogies for engaging younger students in meaningful learning in VR environments. Lastly, VR studies coded also ranged across multiple domains: Biological sciences ($N = 16$), geology and geography education ($N = 3$), engineering and computer science education ($N = 3$), among others. Future studies should consider investigating the effect of this principles VR on learning in the physical sciences and engineering educational domains.

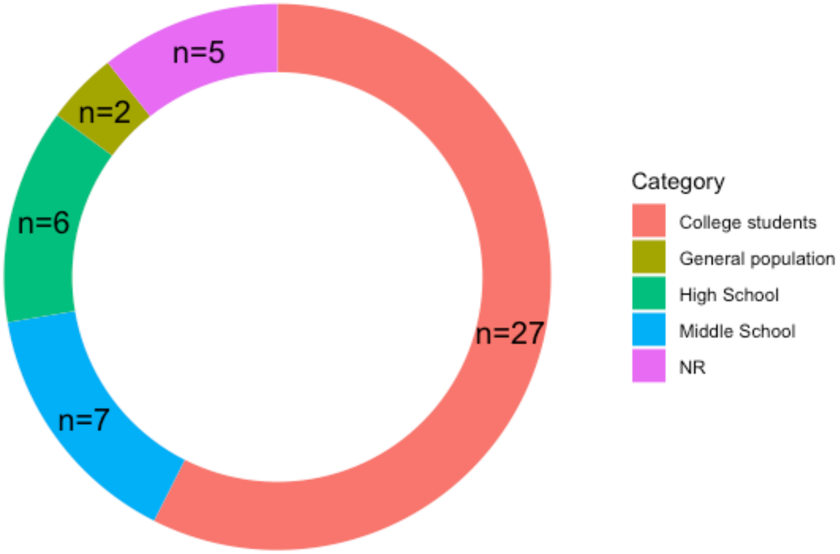

Figure 2.5: Type of learner groups in the reviewed articles
*Source: Developed by author on R

Methodological characteristics: We examined the methodological features of the studies that were coded. A majority ($N = 35$) of the VR studies coded were conducted under controlled laboratory conditions, while 13 studies were conducted as part of regular instructional activities in the classroom. Most of the studies ($N = 32$) used an experimental research design that included a random assignment of participants to treatment and control groups (65%). The remaining 17 studies using a quasi-experimental design that had no random group assignments. Hamilton et al.

(2021) observed a similar trend in review of immersive VR research. Some have argued that lab-based studies lack ecological validity because many typical classroom factors are controlled in laboratory conditions. Since most of the VR studies were conducted under controlled laboratory conditions, it is impossible to establish how relevant the findings of these lab-based studies are to classroom learning. As such, more classroom-based studies are needed to evaluate the generalizability of the findings of extant laboratory-based VR studies. Such studies may also highlight facts about VR implementation that are more relatable to the situations instructors encounter in classrooms.

Furthermore, we examined the analytic approaches of the studies in addressing their research questions, and how they handled sensitivity analysis. An Analysis of Variance (or Covariance) approach was utilized by 63% of the studies reviewed. Seven studies compared treatment and control groups across several continuous variables using the Multivariate Analysis of Variance approach. Six studies analyzed their data using independent samples t-test approach. In five studies, a regression/mediational analytic technique was applied. A small number of studies ($N = 4$) utilized the pre-post design, evaluating test scores before and after VR exposure. Eight studies reported conducting a sensitivity power analysis test prior to their primary analysis. According to our findings, few studies perform or reported pre- or post-hoc sensitivity analysis. The reporting of sensitivity analysis is critical for assuring methodological rigor, improving dependability, and confirming the validity of important findings. Sensitivity analysis is crucial for assessing the robustness of the study’s conclusions based on the primary analysis, and consistency between the primary and sensitivity analysis results can strengthen its credibility (Thabane et al., 2013). In light of this, we urge future studies to conduct and disclose sensitivity analyses.

Methodology features such as assessment instrumentation, study duration, and intervention characteristics were also examined. A majority of the studies coded used multiple-choice questionnaires (MCQ) developed or adapted by the authors to assess outcome measures. For example, some researchers have developed and validated presence scales (Makransky et al., 2017; Schubert et al., 2001; Sutcliffe et al., 2005; Witmer & Singer, 1998). About 60% of the coded articles investigated the learning effects of VR where participants used HMD while the remaining studies focused on VR that did not require HMD. The HMDs used across the studies included the Samsung Gear (e.g., (Meyer et al., 2019)), HTC Vive (e.g., (Zhao et al., 2020)), Oculus VR (e.g., Vogt et al., 2021a)), Zeiss VR (e.g., (Vogt et al., 2021b).

As illustrated in Figure 2.6a, the majority of VR interventions involved situations where learners actively interacted with the learning materials. Whereas learners only observed the VR environment in 19 studies. Figure 2.6b indicates that participants interacted with VR content or environment for 20 minutes or less in 42% of the studies reviewed, while 26% of the studies coded failed to report how long participants received a VR intervention for. Failing to report the duration of exposure to VR interventions can make it difficult to evaluate the effects of duration of VR exposure or intervention on cognitive and non-cognitive effects. For example, longer, as opposed to shorter, exposure may imply longer time on task, or learner getting more authentic learning experiences. On the contrary, the effectiveness of interaction with learning in VR may be masked by novelty effects or disorientations that can be caused by a lack of prior experience with such environments (Alfadil, 2020). To facilitate replicability and ensure methodological rigor, we strongly recommend that researchers endeavor to report the duration of VR interactions, and whether those interactions were based on single or multi exposure.

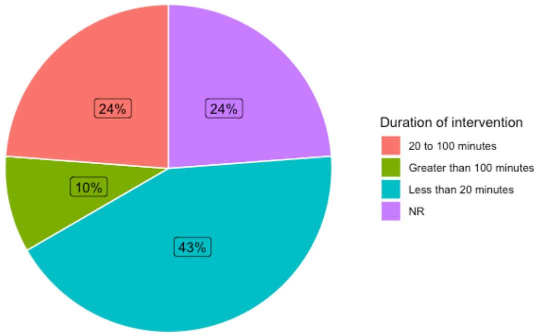

Figure 2.6a: Duration of Intervention

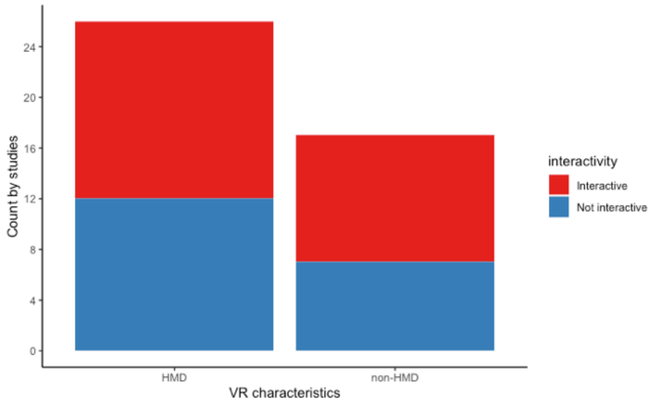

Figure 2.6b: VR types and interactivity

2.6.3 Research Question 3: What learning outcomes are examined by VRLE studies that implemented these design-based principles?

Table 2.4 displays the outcomes reported in the studies reviewed. We extracted thirty-three distinct outcomes, which we classified as measures of cognitive factors, affective factors, cognitive load, or usability. In cognitive factor category, 18 studies measure transfer of knowledge, 18 studies examined retention or memory, 8 studies examined general comprehension, and 8 studies measured learning performance accuracy or efficiency. Very few studies observed subcategories of cognitive outcomes such as application, completion rate, and declarative, conceptual, factual, and spatial knowledge. Our observations were consistent with those reported by authors in similar prior reviews (Bayraktar et al., 2019). In the affective outcomes category, authors assessed presence (8 studies), motivation (7 studies), and enjoyment (7 studies). But we also observed the assessment of other types of affective variables such as emotion, self-efficacy, interest, and flow. Thirty studies examined the effect of VR content on cognitive load, while four studies measured participants' time spent on task. We observed that some studies assessed cognitive load using measures of working memory, attention allocation, and difficulty rating.

From the studies reviewed, we observed that VR research have not explored several cognitive and affective variables that have important implications for the learning experiences with educational technologies. For example, very few studies examined the effect of learning in VR environments on situational interest, spatial knowledge, emotions, and self-efficacy. As such, studies that explore VR effects on these factors are needed in future VR research. Future studies may examine how the design and pedagogical features of instructional VR engender these cognitive and affective variables affect, how they affected when learners' interaction with VR environments. We observed that most studies relied on subjective self-report instruments to measure many of the important outcome variables observed this reviewed. Future studies may also explore the use of eye-tracking device, functional near-infrared spectroscopy (fNIRS), electroencephalogram (EEG), electrocardiogram (ECG) to assess cognitive load assessments (Brunken et al., 2003; Martin, 2014).

2.6.4 Research Question 4: In what ways do these design principles affect cognitive learning outcomes?

Reducing extraneous processing principles

Redundancy Principle: The redundancy principle states that multimedia information presented in redundant forms afford lower learning benefits than if they were presented in non-redundant forms. Five of the studies coded were used to compute the effect of redundancy on learning in VR environments. The median effect size of the redundancy principle on cognitive learning outcomes was Cohen's $d = 0.20$ – indicating that the presence of redundancy improved cognitive learning outcomes across five VR studies (Lines 1-5 of Table 2.5). Specifically, three of studies reported finding a positive effect of redundancy on retention (Baceviciute et al., 2022; Liu et al., 2015; Liu et al., 2021). Baceviciute et al. (2022) examined the learning effects of redundancy in immersive VR environments on medical education. Participants in their study were randomly assigned to a non-redundant auditory only, non-redundant written only, or redundant auditory-written experimental conditions. They found that differences between the groups were statistically significant. Participants in the redundant auditory group outperformed those in the non-redundant auditory group (d = 1.04, Eta squared (η^2) = 0.12). In other different observations, redundancy effect on retention, learning performance accuracy, and comprehension ranged between d = 0.52 ~ 0.57. These findings are consistent with previous multimedia research studies that suggest that redundancy can aid the recall of information when provided through aural representations (Adesope & Nesbit, 2012). We also observed that the effect of redundancy on knowledge transfer ranged between d = - 0.16 ~ - 0.18, and was statistically insignificant (Makransky et al., 2019; Moreno & Mayer, 2002)

Signaling principle: The signaling principle of multimedia learning suggests that incorporating signs or cues, such as arrows and highlights, into VR lessons facilitates learning. Six of the studies coded examined the effect of signaling on learning outcomes (Lines 7-13 of Table 2.5). The effects of signaling on learning in VR across six studies was inconsistent. Three studies found that employing signals in VR improved retention (d = 0.25), knowledge transfer (d = 0.49 ~ 0.71), and learning performance efficiency (d = 0.49). On the contrary, others found no tangible effect of signaling on learning performance (Hwang & Shin, 2018; Nelson et al., 2016). Some recent studies have sought to extend the signaling principle by studying the effects of adding annotations (*annotation effect*) to VR environments (Albus et al., 2021; Vogt. et al., 2021). Albus et al. 2021 examined whether textual annotations enhanced VR learning in biological education. In their study, they divided participants into two groups – a treatment group that featured textual annotations in the form of brief written phrases and a matched comparison group that viewed visual information (pictures). Students who received annotations outperformed the control group on recall ($d = 0.26$, $\eta^2 = 0.04$), and transfer ($d = 0.19$, $\eta^2 = 0.03$), but not on comprehension. On the contrary, Vogt et al., (2021) found that using brief written text labels as annotation had a negligible effect on knowledge tests ($\eta^2 = 0.02$). Although only a few studies have examined the effect of annotations on learning in VR environments, their findings have been consistent with those of studies that examined signaling and annotation effect in other multi-media environment (e.g., (Mason et al., 2013). A recent meta-analysis found that signaling had a positive effect on learning ($g = 0.33$) in multi-media environment (Schneider et al., 2018). Since textual annotations can serve signaling and mapping functions, including them in VR environments can enhance visual search and guide student's attention to important details of VR instructional contents (Ozcelik et al., 2010). However, the relevance of this finding is limited because significant heterogeneity was observed between the studies that were summarized. Hence, we opine that more studies are needed to establish how effective signaling and annotation will be on learning in VR environment.

Scaffolding principle: Like signaling and annotation, some studies explored the effects of incorporating scaffolding to guide learning into VR environment – either by technology-driven navigational aids or pedagogical guidance. Eight of the studies coded examined the effect of scaffolding on learning outcomes. For instance, Mayer et al. (2002) investigated the effect of scaffolding on students' learning of geography in a VR environment. Participants that were scaffolded to collect geographical data performed better on knowledge accuracy (*d* = 0.41, η^2 = 0.05) and knowledge transfer (*d* = 0.85, η^2 = 0.19). Similarly, other studies have shown that offering direction through guided exploration in VR environments leads to enhanced learning benefits, fewer errors, and enhances the rate of task completion. (Chen & Ismail, 2008; Ullah et al., 2016). Conversely, a few studies reported that guidance had no effect on learning in some contexts (Nelson, 2007; Topu & Goktas, 2019). Baydas et al. (2015) reported that providing guidance had a negative effect on knowledge retention (*d* = -0.61, η^2 = 0.10). Despite the few negative or negligible findings, a summary of the empirical evidence suggests that providing scaffolds enhance the learning experience in VR sessions (median *d* = 0.48). We observed that only one study reported on the effect of technology-driven scaffolds – navigational aids in VR (Burigat & Chittaro, 2016). Future studies may further explore the effects of providing navigational aids to facilitate learning in VR.

Managing essential processing principles

Modality principle: The modality principle posits that people learn more effectively when instructional materials are presented in graphical and audio narration formats rather than graphical and written text. A study by Moreno & Mayer (2004) showed that modality had a positive effect on knowledge retention and transfer of biological concepts. Participants achieved higher retention (median *d* = 0.8) and knowledge transfer (median *d* = 1.08) when learning material was presented as sound instead of on-screen text. However, the findings of some other studies failed to confirm these results. For instance, Erlandson et al. (2010) found no statistically significance modality effect on content and procedural knowledge after students completed a science inquiry session. Contrary to the modality principle, Do and Moreland (2014) observed that students in an auditory condition made fewer errors in learning performance and accuracy than those in the visual condition. Despite the contradictory findings, there are reasons to believe that the modality effect can be relevant to learning in VR environments under the right conditions (Lines 30 of Table 2.5). Prior studies have shown evidence that the modality principle enhances learning under controlled laboratory settings (Ginns, 2005; Reinwein, 2012). Future studies can explore the transferability of this findings to learning in formal and informal settings that have better ecological validity.

The Pre-training principle: Providing pre-training has been found to foster essential processing and enhance learning in multi-media environment. Pre-training has been shown in some studies to enhance knowledge retention and transfer scores, and to improved learning experience (Howard & Lee, 2020; Meyer et al., 2019; Petersen et al., 2020). For example, Meyer et al., (2019) found a strong pre-training effect on retention and transfer when students were provided pre-training opportunities that familiarized them with names and essential concepts before they participated in a VR activity. Furthermore, we discovered evidence of the pre-training principle being applied to learning outcomes in VR environments (median $d = 0.59$). On the contrary, other studies reported that pre-training had negligible effect on learning in some contexts. For example, Petersen reported that pre-training had no effect on declarative knowledge (Petersen et al., 2020). Similarly, Meyer and colleagues reported that pre-training effect disappeared when learners were tested on delayed recall and transfer tasks. In summary, the evidence suggests that pre-training has a positive effect on learning in some, but not all VR learning conditions (Lines 31-34 of Table 2.5).

Sequencing Effect: Vogt and colleagues examined whether adequate sequencing of VR lessons can foster deep learning processes. They investigated whether the use of VR animation, followed by a verbal information (auditory text) was beneficial for learning. Participants achieved higher declarative knowledge scores ($d = 0.67$, $\eta^2 = 0.14$) when VR material was presented as animation first instead of auditory text. However, no effect was observed for comprehension and knowledge application (Line 35 of Table 2.5). The study highlight that sequencing VR presentations may aid learners to manage essential processing, which could free up cognitive capacity to engage in more generative processes.

Segmenting Principle: The CTML proposes that segmenting information can help learners to manage complicated multimedia contents – thus facilitating essential processing (Mayer, 2014). Parong and Mayer (2018) explored using the segmenting principle to foster essential processing in VR environments. They reported that students who received VR lessons in short segments outperformed those that received the VR lesson in continuous format on factual knowledge tests (Line 36 of Table 2.5).

Fostering generative processing principles

Personalization principle: The use of conversational and personalized language has been found to enhance learning in multimedia lessons. Mayer's (2020) observed a very large personalization effect (median $d = 1.0$) on multimedia learning across 15 studies. While there has been robust evidence for the personalization principle across multiple multi-media learning studies, the personalization effect was only reported in one VR study (Lines 37 of Table 2.5). Moreno and Mayer (2004) found that using personalized language in in VR media had a large effect on knowledge retention ($d = 0.77$, $\eta^2 = 0.2$) and transfer ($d = 1.64$, $\eta^2 = 0.46$).

Imaging Principle: Researchers have observed that the inclusion or lack of inclusion of visible instructional agents in multi-media or VR media has no significant impact on learning (Petersen et al., 2021). Mayer (2020) found a negligible effect (median *d* = 0.20) of agents in a review of seven multi-media learning studies that examined the effect of imaging on learning. Because several empirical studies have demonstrated that including a speaker's image had a negative or negligible effects on learning, Mayer concluded that adding a speaker's image to a multimedia lesson does not improve learning outcome. A study that examined the imaging effect on learning in VR environment found that including a speaker's image as a sophisticated pedagogical agent in VR media did not enhance factual learning (Refer to Line 38 of Table 2.5).

Embodiment Principle: The embodiment principle in multi-media learning literature focuses on the presence or absence of pedagogical agents' gestures in learning settings and has been shown to have some beneficial effect on learning. The principle asserts that pedagogical agents with human-like movements or gestures facilitate learning by providing social cues that motivate learners to engage more deeply with learning material (Mayer, 2020; Petersen et al., 2021). In our review of VR studies, we found empirical support for the embodiment effect (median *d* = 0.22) in VR learning (Liew et al., 2016; Makransky et al., 2019; Petersen et al., 2021) – two studies reported a positive learning effect of the embodiment principle on learning in VR environment (Refer to Line 39-41 of Table 2.5). However, Petersen et al (2021) found in their study that including highly behavioral embodied agents resulted in an increased sense of social presence but had a negative effect (*d* = - 0.37) on learning. Invariably, participants that learned with highly visual and dynamic pedagogical agents performed worse than those who used static and low visually aesthetic agent. These findings highlight the need for caution when considering how to incorporate pedagogical agents in the design of VR learning media. The finding also highlights the need for more studies that investigates factors that moderate the effects of embodiment on learning in VR environments.

Immersion principle: The principle asserts that individuals do not necessarily learn better when in more immersive VR media. The principle has been the most studied among extant VR media learning research. We observed a small negative effect (median $d = -0.10$) of immersion on learning across 16 studies that examined the effect of immersion on learning in VR. (Refer to Line 45-60 of Table 2.5). Seven of the studies that examined the effect of immersion on learning found a small but negative effect of immersion on VR learning. However, six of the studies found no difference in cognitive learning between highly immersive and less immersive VR media. The immersion effect in VR media is comparable to those reported in Mayer's review of immersion effect in other multi-media learning environments. Mayer (2020) reported observing a small and negative immersion effect (median $d = -0.10$) on knowledge transfer tasks across the nine multi-media learning studies reviewed. In Mayer's review of multi-media studies and our review of VR studies, the negative immersion effect on learning was small. However, neither reviews could ascertain whether these small and negative effects had statistical and practical significance for learning. On the one hand, one may conclude that immersive media may not always be beneficial for learning, as some have argued (Parong & Mayer, 2018). However, given that the observed negative effects are minuscule, there is need for future studies to discriminate between which kinds of learning outcomes can be better enhanced, and which are hurt, by high immersion (or immersive media). Furthermore, we propose that additional research is needed to ascertain how design and pedagogical features of immersive media research studies contribute to the immersion effect on the different kinds of learning outcomes that had been reported in extant multi-media and VR learning literature. Future studies may also explore the variance of the immersion effect on learning across different domain-specific learning outcomes.

Collaborative principle: Two studies examined the use of collaborative activities to facilitate generative learning (Cho & Lim, 2017; Tseng et al., 2020). Across the two studies (Refer to Line 43-44 of Table 2.5), we observed that VR participants who engaged in collaborative learning activities outperformed VR learners that worked individually on cognitive learning outcomes (median $d = 0.43$). Some researchers have proposed the social agency hypothesis to explain the collaborative learning effect. Proponents of this hypothesis argue that because of the social interactions that occur during collaborative learning situations, learners who engage in collaborative learning activities are primed to deeper cognitive processing and engagement and are better motivated to learn. Tseng et al. (2020) found that participants who worked collaboratively performed better on long-term retention of knowledge. They argued that the collaborative effect was likely because students who worked collaboratively receive personalized and tailored feedback from their peers. Such peer feedback can become deeply entrenched in their long-term memory.

Generative activity principles: In addition to the foregoing, some studies reported the effect of certain generative activity principles described by Fiorella and Mayer (2021a): two studies found that summarizing activities had positive effect (median $d = 0.56$) on learning (Parong & Mayer, 2018; Zhao et al., 2020); two studies found that the use of elaboration or prompting had a positive effect (median $d = 0.47$) on learning (Vogt et al., 2021b; Vogt. et al., 2021); two studies reported finding a positive practice testing effect (median $d = 0.35$) on learning (Parong & Mayer, 2021a, 2021b); and one study reported that enacting had a positive effect on procedural knowledge (*d* = 0.78, η^2 = 0.14) and transfer (*d* = 0.62, η^2= 0.09). Furthermore, we observed that learning by teaching and planning activities were used as generative learning activities (Fiorella et al., 2019; Klingenberg et al., 2020; Nie & Wu, 2020). Two studies found that the use of learning by teaching activity had a positive effect (median *d* = 0.41) on learning (Refer to Line 64-66 of Table 2.5). For example, Klingenberg et al (2020) examined the efficacy of adding a learning by teaching activity to a VR exercise. They found that participants who engaged in the learning by teaching activity during a VR learning exercise performed better on knowledge transfer (*d* = 1.26) and retention scores (*d* = 0.6) than those that did not. Their study highlights that learning through teaching can activate generative processing because learners can better reflect on the material, which may aid their learning. Nie and Wu (2020) examined the effect of including planning activities in VR lessons as a generative learning activity. Their study found that students who engaged in planning activities that were related to learning the material in VR environments scored better on knowledge transfer tasks (*d* = 0.77) and task completion time (*d* = 0.48) than those that did not. Their study highlight that planning exercises may engender generative processes that enhance learning in multi-media and VR media. For example, students who are required to plan how they would resolve a problem would likely consider all the important facts or information about the problem, identify, and organize appropriate steps that would be required to ensure they can tackle the problem.

Overall, our observations suggest that generative activities improved learning across nine studies. Our findings were comparable with those observed the review of generative activities in multimedia learning research (Fiorella & Mayer, 2016). However, we discovered that many of the generative activities they described had not been investigated in VR contexts. We recommend that future studies investigate how to incorporate many of these generative activities to enhance learning in VR instruction as well, as to examine the magnitude and direction of their effects on learning in VR.

2.7 Potential factors that moderated the learning effects of the design and pedagogical principles in VRLEs.

In the previous section, we summarized the major effects of the different design and pedagogical principles for multi-media learning on the learning outcomes that were described in the VR studies we reviewed. Our goal in this section is to briefly summarize some factors that moderated the effects of the different design and pedagogical principles on the learning outcomes described in the studies we examined. We coded the studies reviewed for contextual and methodological study characteristics, learner differences, emotional, motivational, cognitive processing variables to identify these moderating factors.

Redundancy Principle: Across the VR studies we reviewed, we observed that the learning effects of the redundancy principle may be moderated by variables associated with study contexts and conditions. For example, we observed across five studies that examined the redundancy principle that most studies conducted under controlled (i.e., laboratory) conditions found negligible effect of redundancy on learning outcomes. On the contrary, a reverse redundancy effect was observed in studies that were conducted in actual classrooms (i.e., students who got redundant contents in classrooms that included VR activities outperformed those who did not). Since most learning actually occur under less controlled environments, this phenomenon begs the need for further investigation of the boundaries of the redundancy effect, especially in real classroom learning contexts.

We observed that the redundancy effect may be impacted by extraneous factors that often exist in typical classrooms (Liu et al., 2015). For example, Liu and colleagues opined that noises from within and outside the classroom and other student behavioral responses could have distracted learners and exacerbated the redundancy effect on learning in their study (Liu et al., 2021). Liu et al (2015) further argued that the interference of external noise sources could introduce unwanted signals that overloaded leaners' limited processing channel and inhibit learning. Hence, it becomes rather challenging to process redundant instructional information along with 'noisy' interferences in the learning environment.

A reverse redundancy effect on learning outcomes is often observed in VR media, contrary to the redundancy effect that is often observed in traditional multi-media environment. Unlike the traditional multi-media environment, VR media is typically immersive in nature. Additional VR environments provide a greater sense of presence, immersion, and agency than the traditional multi-media environment (Makransky & Petersen, 2021). But to put our reverse-redundancy observation in context, we observed that no significant redundant effect on learning was detected when participants actively interacted with the learning content in VR environments (Baceviciute et al., 2022; Makransky et al., 2019; Moreno & Mayer, 2002). Contrariwise, a reverse redundancy effect was observed in studies where participants did not interact with the content of the VR media. Future research of the redundancy effect in VR environment may further explore the consistency of these observations.

Lastly, it was observed that the degree of the correspondence between narration and text may moderate the redundancy effect on learning. For example, Albus et al. (2021) suggested that using short texts that repeats the message of a narration or visual information can aid encoding, enhance semantic processing and facilitate knowledge retention. This observation was also supported in a meta-analysis of verbal redundancy (Adesope & Nesbit, 2012). Future research could explore how these factors affect the redundancy effect and attempt to isolate factors that confound the redundancy effect on learning.

Signaling (cueing) principle: Factors that affected or constrained the effect of signaling or cueing on learning in VR situations across four studies included cue frequency, animation rate, and instructional modality. Hwang and Shin (2018) reported that the recurrence or frequency of signals reduced extraneous cognitive load. They argued that learners in 3D environments may perceive frequent cues as motivating aids rather than as cognitive strains. This contradicts previous observations that providing excessive verbal signals in multimedia environment may cause cognitive stress rather than guide attention (Mayer, 2020). Albus and colleague' study suggests that students in VR learning environments may perceive cues as part of the immersiveness of the VR environment and process them differently than they would in other non-immersive multimedia environments (Albus & Seufert, 2022; Hwang & Shin, 2018). In Shin and Park (2019), providing signaling over an extended period may mitigate cognitive load. Consequently, their study indicates that frequency of signal or cues occurrence may be an important boundary condition for signaling in a VR environment.

The studies by De Koning et al. (2007) and Hwang and Shin (2018), suggested that the speed of animation' may moderate the cueing effect on learning. The studies asserts that learners may struggle with grasping learning content in VR environment if the instructional content is fast paced. On the contrary, advocates of the apprehension principle have argued that slower-paced animation of learning content offer learners more control and allow them enough time to grasp the instructional material (Tversky et al., 2002). Lastly, Hwang and Shin (2018) claimed the format of signaling may have implication for learning. They had used a hybrid of static or non-dynamic visual signals in dynamic animation in their study. They argued that doing so resulted in a split attention in learners and caused them to struggle with assimilation. These observations may portend potential boundary conditions of the signaling or cueing effects that should be further explored in future VR studies.

Annotation Effect: It was observed across the studies reviewed that the effect of annotation on learning outcomes in VR environment can be affected by the type of annotation, cognitive processing, learner characteristic differences, and the fidelity of representation of VR content. Vogt et al. (2021) observed in their study that the kind of information that an annotation conveys and how it is presented may influence its learning effect. For example, short text annotations that are positioned closely to their corresponding visual representations can provide mapping support and improve learning. Schnotz and Bannert (2003) reported that annotations that were closely positioned to the content they referenced helped students to mentally connect and organize related knowledge and had a positive learning effect on knowledge application. However, the text annotations may not promote high-order learning outcomes if they are merely a repetition of their corresponding verbal and visual representations (Albus et al., 2021). Additionally, the extent to which annotations promote learning depends on the spatial distance of the text to the visual or verbal information they reference (Albus et al., 2021; Austin, 2009; Varol & Erçetin, 2021). VR environments with very high fidelity of representation may have a high intrinsic load – and be complex for learners to process. Hence, annotations may be particularly helpful for aiding learning in such VR environment (Richter et al., 2016).

Including annotations had no substantial influence on extraneous load across two studies examined. Meanwhile, there were indications that including annotations fostered generative processing (Albus et al., 2021). This is consistent with previous observations that annotations fail to reduce extraneous processing (De Koning et al., 2009; Mayer & Fiorella, 2014). Annotation provide mental mapping support that aid knowledge organization (Vogt. et al., 2021), and facilitate building a coherent mental representation of visual and verbal information of multi-media material (Mayer et al., 1995). Furthermore, annotations can direct learners' attention to the most essential information in VR contents, (Gegenfurtner et al., 2011; Mayer et al., 1996). Hence, it may be considered as an example of a generative processing principle.

Lastly, we observed that the annotation effect on learning outcomes was moderated by some learner characteristics (Seufert, 2003). For example, learners who are less intrinsically motivated (Vogt. et al., 2021), or have a low prior knowledge (Akyel & Erçetin, 2009; Mayer et al., 1995) are more likely to benefit from annotations than other students. It also, appeared that the annotation effect was greater for surface-level learning outcomes than deeper-level learning outcomes (Albus & Seufert, 2022; Albus et al., 2021).

Scaffolding Effects: Across the studies reviewed, we observed scaffolding VR learning experiences by providing specific guidance, persistency in guiding, and using navigational aids may moderate learning outcomes. The effect of providing guidance on learning outcomes could depend on the form of guidance or scaffolding learners were given. For example, providing visual guidance, such as pictorial scaffolds, tend to be more helpful than verbal scaffolds (Mayer et al., 2002). Prior multi-media learning study have reported that providing visual guidance aided visuospatial cognition, especially where learning involves for coherent mental representations of high spatial contents (Eitel et al., 2013). This may be especially important for activities that require a high level of spatial reasoning, such as geology and engineering. Contrariwise, verbal scaffolding may be less effective to facilitate the learning of highly spatial content (Mayer et al., 2002). Scaffolds may come in the form of pedagogical-driven guidance and technological-driven navigations. Our review indicates that the usefulness of scaffolding or guidance to learning may depend on which type was provided. Providing navigational aids alone can reduce extraneous load, enhance schema representation, and improve learning effectiveness (Chen & Ismail, 2008; Rouet & Potelle, 2005). Learners who have extensive prior exposure to VR environment may find the navigational aids less impactful on learning than those with no or little prior exposure (Chen & Wang, 2009). As such, highly experienced learners in VR may be able to balance the cognitive load engendered by the navigational aids better than novice VR learners. Conversely, providing pedagogical guidance to learners with less VR experience or exposure may have a significant effect on learning. However, providing pedagogical guidance concurrently with technology driven navigational aids may induce a cognitive overload which could inhibit learning (Baydas et al., 2015). In addition, the persistence of using guidance tended to enhance students' understanding in science context (Nelson, 2007). Students may be particularly motivated to deeply engaged in exploratory or discovery-based VR experiences if guidance and navigational aids are consistently provided.

Modality principle: According to Mayer (2020), the modality principle facilitates essential processing that foster higher-order learning outcomes such as knowledge transfer and application of the instructional material. Consistent with this view, we observed across two studies that the modality effect was stronger for knowledge application or transfer tasks than on knowledge retrieval or retention tasks in VR environment (Moreno & Mayer, 2002 Exp 1, 2). Further, we observed that the modality effect on learning was significant when learners interacted in a tangible way with the VR content and environment (e.g., Moreno & Mayer, 2002). However, modality effect on learning was non-existent when learner did not interact with, but only observed VR content and environment (e.g., Do & Moreland, 2014). We recommend that future research investigate how interaction with VR systems moderate the modality effect on learning with VR.

Pre-training principle: Pre-training was observed to have tangible effects on higher-level cognitive outcomes, such as knowledge transfer, but not on lower-level outcomes like declarative knowledge (e.g., Petersen et al., 2020). Mayer and Fiorella (2021) argued that pre-training facilitates essential processing that necessitates deeper understanding of instructional contents (Mayer & Fiorella, 2021). The evidence suggested that pre-training was more beneficial at immediate post-intervention tests but did not reflect on delayed tests performance. In essence, pre-training effects seem to disappear over time (e.g., Meyer et al., 2021). Pre-training was also found to enhance students' self-efficacy and confidence in their ability to interact with and learn in visually complex VR environment.

Embodiment principle: One of the studies reviewed found that using highly behavioral and visually appealing pedagogical agents to mimic real life instructional guides in VR environment increased participants sense of social presence (Petersen et al., 2021). Such embodiments have been shown in extant multi-media learning literature as contributing a 'persona effect' (Mayer & DaPra, 2012; Moreno et al., 2001) because they provide social cues that may stimulate social reactions in learners (Fiorella & Mayer, 2021b; Mayer et al., 2003). However, we observed across three studies that examined the embodiment effect that higher social presence does not necessarily imply increased factual understanding. For one, the supposedly increased social presence that an agent engenders through its high behavioral realism may increase the amount of information that learners need to process, and thus cognitive load. By implication, increasing exposure to highly behavioral visual agents may not necessarily enhance the learning experience. On the contrary, a less behaviorally and visually embodied agent may be less attention grabbing, and thus less distracting for learning in VR environments.

We observed from the studies reviewed that learner's perception of virtual pedagogical agents could also affect their perceptions of the learning environment and experience. For example, Liew et al. (2016) observed that participants who interpreted the pedagogical agent's expression as misleading, reported a negative emotions about their learning experience. To corroborate this finding, prior studies has shown that some learners have a negative perception of embodied voice in multimedia environment (Mayer, 2020). For example, some learners tend to associate negative social cues with machine voice and view them as distractive and unhelpful for learning (Atkinson et al., 2005; Mayer & DaPra, 2012; Mayer et al., 2003). Similarly, we observed from the studies reviewed that the facial expressions of embodied pedagogical agents can impact learners' emotions and motivation. For example, learner responded with joyful emotions when they perceived agents as friendly and real, but perceptions of fake or unpleasant looks evoked negative reactions.

Lastly, we observed that learners' perception of a pedagogical agent's appearance seemed to have moderated the learning outcome in one study. A positive learning effect of embodiment was observed when the embodied agent's appearance matched those of the learner. For example, Makransky et al. (2019) found that girls in their study learned better with female-like embodied agent, whereas boys learned better when they had a male-like embodied agent. In addition, they found that boys exhibited a stronger social presence toward a female pedagogical agent than girls did to a female agent. However, this increased sense of social presence did not result in enhanced learning outcomes. The multi-media literature had suggested gestures, body movement, and facial expressions as boundary conditions for the embodiment principle (Mayer, 2020). However, the evidence in this review suggests we may need to consider agents' appearances as a potential moderator of learning outcomes in multi-media and VR media environments. Future studies may further investigate how emotions, social cues, gender, and learner characteristics influence the effect of embodiment in VR learning.

Immersion Principle: The evidence overwhelmingly suggests that highly immersive media facilitated higher degrees of presence (Makransky et al., 2019; Makransky et al., 2020; Moreno & Mayer, 2002), enjoyment (Meyer et al., 2019), emotional arousal (Parong & Mayer, 2018; Parong & Mayer, 2021b), motivation (Di Natale et al., 2020), and self-efficacy (Makransky et al., 2019). However, highly immersive VR environments can cause distractions that increase extraneous load and can cause a cognitive overload (Parong & Mayer, 2021a). Although high immersive VR can increase learners' sense of presence, it is also the case that its "seductive" content can increase extraneous cognitive processing rather than generative processing (Mayer, 2020).

We observed that doing generative activities may influence the immersion effect on learning in VR environments. For example, participants who were involved in planning exercises related to a circuit simulation task performed better on knowledge transfer tasks (Nie & Wu, 2020). Similarly, other studies reported that highly immersive VR environment where more effective for learning than less immersive VR when its implementation included the use of pedagogies of active or generative learning (Meyer et al., 2019; Liu et al., 2021, Makransky et al. 2020). Certain design decisions can impair the effectiveness of Immersive VRs to support learning. For example, Parong & Mayer (2021) argued in their study that system-paced VR content violates the segmenting principle of multi-media learning and may have deleterious effects on learning.

The learning effect of immersion were more pronounced in learning contexts that involved higher-order thinking or skill training. For instance, the immersive VR may have a significant effect on the learning of procedural knowledge in engineering education contexts. The immersion effect on learning has also been found to be moderated by domain prior knowledge (Barnidge et al., 2022), age (Plechatá et al., 2019), novelty or unfamiliarity with VR technology or control interfaces (Hamilton et al., 2021). There is a need for exploring the factors that moderate the immersion effect on learning in VR environment.

Generative activity principles: Evidence from the studies reviewed indicated that generative learning activities facilitates learning in VR environments. However, this effect tended to be influenced by the time spent engaging in generative activities, and the kind of generative activities learners engage in while in VR environment. For instance, Fiorella et al. (2019) observed that many of the participants in their study spent so much time on irrelevant tasks while navigating a virtual space. Such irrelevant activities fail to engender generative processing.

In addition, activities that foster generative processing tend to be more efficacious for higher-order, than for lower-order learning outcomes. For example, involvement in collaborative activities (a type of generative activity) had significantly larger effect on tasks related to knowledge application and transfer than on tasks related to declarative knowledge and knowledge retrieval. Similar positive learning effects were observed when VR learning included generative activities such as: learning by teaching (Fiorella et al., 2019), enactment (Makransky et al., 2021), practice testing (Parong & Mayer, 2021b), prompting (Vogt et al., 2021b), and planning (Nie & Wu, 2020).

In addition to learning benefits, generative activities embedded in VR learning contexts may reduce cognitive overload. Zhao et al. (2020) reported that students who participated in VR learning that included summarizing activities reportedly experienced lower cognitive load than those that did not. More future studies that explore various modalities for integrating different generative learning activities to enhance the VR learning experience are needed.

2.8 Implications for future research

This systematic review revealed several gaps in our knowledge of the applications of traditional multi-media design and pedagogy principles in VRLEs. The review also highlighted some shortcomings in previous studies that have examined the effects of these evidence-based principles on learning in VR contexts. First, we observed that a majority of the studies reviewed were conducted in Europe (38%) and the United States (31%). Similarly, a large share of the studies was conducted on participants in the biological sciences, and most of the participants were college students. Replications of existing studies under new studied contexts, and studies that explore new frontiers by examining the effects of the different design and pedagogy principles of multi-media on learning in VR contexts are urgently needed. Such studies may explore the learning effects of VR across a diverse cultural context (e.g., Africa), age groups (e.g., with younger learners), and domain (e.g., engineering education). Future studies can further explore the boundary limits of the learning effects of these pedagogical and design principles of multi-media learning in VR environment.

Many of the studies examined in this review tended to rely on subjective, rather than objective, instruments to measure the outcome variables they examined. For example, most assessments of cognitive load were based on self-report instrument. Future replication studies that utilize objective measures of brain functions that indicate cognitive load can corroborate observations made in existing studies. While studies that use more objective measures of cognitive load may require specialized equipment, they could validate the findings of subjective or self-report measures of cognitive load. We also recommend that researchers should report salient characteristics of their studies (such as, sensitivity analysis, duration of VR intervention, and other intervention characteristics) than enhance replicability of their studies. Reporting such methodology features will necessarily demonstrate scientific rigor and strengthen the validity of reported findings.

Many of the studies included in this review investigated design-focused VR experiments and were conducted under very control laboratory settings. To strengthen the relevance and ecological validity of reported findings, replication of prior experimental studies of learning in VR conducted under typical classroom conditions are highly encouraged. More future studies should explore both design and pedagogical principles for managing extraneous, essential, and generative processing in VR learning environments.

The multi-media learning research literature proposes different design principles that can be relevant to learning in VR. However, learning in many VR environments can elicit emotive responses that may or may not be beneficial to learning (Parong & Mayer, 2021a). Even though certain affective and motivational factors may impact how students engage with learning in VR environment, there are scarcely any studies that examine the implications of multimedia design and pedagogies principles on relevant achievement emotions. For example, instructional content in VR environment may trigger situational interest, enjoyment, or influence learner's perception of task value among others. It is also not unlikely that interacting with VR content foster self-efficacy for learning. We call for more studies that explore the implication of design and pedagogy principles on these and other relevant affect and motivation variables that may have implication for how learners are motivated to learn with VR, especially in STEM fields. Additionally, we observed that most of the studies reviewed focused on the effects of VR media and pedagogy principles on knowledge retrieval and transfer, mostly in laboratory and classroom settings. Future studies can explore these effects on skill training and procedural knowledge acquisition in formal and informal learning context – including workforce development research.

This review highlights that there has been an increasing number of empirical studies that examine evidence for the multi-media design and pedagogy principles on learning in VR contexts. However, the number of published VR studies that are grounded in established evidence-based principles relative to those in the traditional multi-media learning literature is quite low. In fact, few studies investigate the applications of the principles of generative learning in VR environments. Furthermore, studies are yet to examine the applications of the self-explanation, mapping, and drawing principles for learning in VR environment. However, future studies that focus on these applications may inform educators and instructional designers on how to design and implement VR environments for effective learning. Examining the mutual effects of design and pedagogic principles on enhancing VR learning in specific domains could be a fruitful and rewarding research direction in the future.

In this systematic review, we identified a number of factors that have the potential to influence the design and pedagogy of learning in VR environments. Based on the current state of the VR learning literature, there is an urgent need to identify evidence-based practices for VR learning in formal and informal context. Such evidence must be the result from methodologically rigorous studies that are grounded in multi-media and relevant learning theories and principles. Future studies may also examine the main and interaction effects of cognitive, affective, and demographic factors that moderate the instructional efficacy of VR learning in different contexts. Such studies may use factorial study designs that systematically manipulate and combine these variables both under laboratory and classroom-based studies. The totality of the findings of such studies may highlight the boundary conditions of different factors of design and pedagogy that are associated with learning in VR media and provide a road map for evidence-practices for fostering effective pedagogy and learning in VR environments.

2.9 Limitations

We recognized a few limitations of this systematic literature. First, only particular databases (Web of Science, Computer Source, and PsycINFO) were used to gather articles, limiting the potential number of possible studies that were retrieval. Furthermore, it is not unlikely that we may have missed a handful of relevant VR study that may have been published after this analysis began. We analyzed learning effects using median effects which does not account for the weight each study contributes, neither does it account for heterogeneity of the effects observed between studies. As a result, we acknowledge that the aggregate effects for the principles discussed in this review should be interpreted cautiously. Nonetheless, our use of the median effect is consistent with past systemic evaluations of multimedia learning research

(Mayer, 2022, Fiorella et al., 2016). Furthermore, there are not sufficient studies to conduct a meta-analysis of many of the effects observed in this systematic review.

Because of the issues highlighted above, we were unable to conduct analysis to determine the statistical significance of the moderator variables identified in this review. Future study could employ meta-analytical procedures to report pooled effects that can provide a more precise quantification of each principle's effect. Future research could also explore the effects of cognitive-affective multimedia principles on motivational and affective variables, as only cognitive learning outcomes were examined in this review. The current review focused solely on VRs application in formal education contexts. Future studies might also examine the effects of these multi-media learning principles on learning in other environments (i.e., augmented reality, mixed reality, game-based learning) and compare the effects of these evidence-based principles on learning in each setting. Finally, we limited our focus on design and pedagogical principles described in the multimedia, cognitive, and generative learning research literature. We acknowledge that there are more design principles (e.g., embodied cognition design principles) for VR learning that can be explored in future review and empirical studies. The scope for future systematic review could be expanded to incorporate other relevant design and pedagogy principles.

2.10 Conclusions

This systematic review literature review examined the learning effect of multi-media design and pedagogical principles on in educational VR environments. Based on the review of 65 studies, we answer questions about the demographics, contextual and methodological characteristics of studies relevant to this review. We also identified the design and pedagogy principles that are used to enhance cognitive processing and promote learning in VRLEs. The reviews showed that has been a growing interest in employing design and pedagogical principles of multi-media learning to facilitate the designs of VRLE. The studies showed that transfer, retention, presence, and cognitive load are frequently measured outcomes. However, motivational variables, such as situational interest, spatial knowledge, and metacognition have been understudied. The immersion was the most investigated design principle in VR intervention studies, while generative activity principles received little attention.

The contextual characteristics of review studies, including country, journal, learning domain, and education level were examined. This review revealed that many of the studies were conducted by European researchers, used college students as participants, and were situated within the biological sciences learning domain. We found that most of the studies reviewed were conducted under laboratory conditions (73%), and most involved the use of HMDs (60%). Furthermore, we found that participants engaged in interactive VR activities, used subjective measures to assess outcome measures, and had a short duration of VR exposures. Most studies used Analysis of Variance (ANOVA) analysis approach (63%) to determine whether group differences were statistically significant.

The review found empirical support for the learning effects of many of the multimedia design and pedagogical principles to facilitate cognitive processing and enhance learning in VR. For example, we observed that interventions that included pre-training exercises before exposure to VR activities improved learning. We also found that incorporating generative activities into VR improves conceptual, procedural, and transfer outcomes. The review will be informative for designing VRLEs that ensure a positive learning experience. The results may also inform researcher in the educational technology research community about the relevance of multimedia learning principle to VR learning. The knowledge gaps identified in this review could provide direction for more empirical research of the design and pedagogies of effective VR learning. Finally, the review can inform educators who wish to implement VR to facilitate the classroom curriculum experience.

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Table 2.1: Inclusion and exclusion criteria

Inclusion Criteria	Exclusion Criteria
Studies at any educational levels and training programs	Studies not publicly available online or not indexed by databases used.
At least one evidence-based principle grounded in cognitive and generative theories.	Studies that did not use VR i.e., augmented reality, mixed reality, computer-based
Article was peer reviewed	Non-English studies
Published not earlier than 2000	Articles is not a review, meta-analysis, editorial commentary, or opinion pieces
Article is an empirical study and contains sufficient descriptive statistics reported for effect size	Qualitative and theoretical studies
Measured outcomes must have cognitive (i.e., recall, transfer, procedural, conceptual) learning	Studies focusing on only usability, ease of use or technology acceptance.

Table 2.2: Countries that have conducted evidence-based principles in VR environments

Continent	Country	*n*	%
Europe	Denmark	10	
	Germany	6	
	Turkey	1	
	Italy	1	
	Total	18	37.50%
North America	USA	15	
	Total	15	31.25%
Asia	Malaysia	3	
	Taiwan	3	
	China	2	
	South-Korea	2	
	Pakistan	1	
	Singapore	1	
	Total	12	25.00%
Not reported	NR	3	6.25%

Table 2.3: Description of evidence-based design and pedagogical principles in VR

Principle	Description
Redundancy	Students learn more effectively from VR contents that are presented in non-redundant forms (i.e., incorporate graphics and narration) rather than redundant forms (i.e., graphics, narration, and on-screen text)
Signaling	Students learn more effectively when VR contents include cues, annotations, and visual highlights
Scaffolding	Students learn more effectively when they are scaffolded by using technological navigational aids or pedagogical guidance
Modality	Students learn more effectively when VR contents are presented in two modalities (i.e., use meaningful images with narrations) rather than a single modality (i.e., on-screen text with images)
Pre-training	Students learn more effectively when they are familiar with key concepts and terms of an instruction material before the VR activity
Sequencing	Students learn more effectively when VR contents are presented in sequential and logical steps (i.e., animation followed by auditory text)
Segmenting	Students learn more effectively from VR activities that are broken down into clear and meaningful segments or phases, rather than uninterrupted presentations

Personalization	Students learn more effectively when VR contents are presented in conversational language using personal pronouns rather than when presented in rather than direct and formal language
Imaging	Students learn more effectively when pedagogical or embodied VR agents are excluded from the VR activity than when they are included
Embodiment	Students learn more effectively when highly behavioral pedagogical or visually aesthetic embodied VR agents are included rather than when they are low behavioral pedagogical or visually aesthetic embodied agent
Immersion	Students do not necessarily learn more effectively with more immersive medias than lower immersive media
Collaborative	Students learn more effectively when they participate in collaborative learning activities that encourages interaction and feedback
Generative activity	Students learn more effectively when they engage in generative activities in VR (i.e., summarizing, prompting, learning by teaching, practice-testing, prompting, enacting, planning)

Table 2.4: Learning outcomes from the reviewed studies

Cognitive	***n***	**Affective**	***n***	**Cognitive load**		**Usability**	***n***
Learning Accuracy (Efficacy)	8	Emotion	2	Time spent on task	4	Perception of learning environment	1
Transfer	18	Motivation	7	Perceived or self-reported Cognitive load	13	Usefulness/Ease of use/ Behavioral intent to use	3
Completion rate	2	Enjoyment	7	Workload or Mental effort	3		
Retention (Recall)	16	Self-efficacy	3	Attention distribution	2		
Learning performance (Knowledge) scores	4	Presence	8	Difficulty rating	1		
Declarative knowledge	3	Attractiveness	1	Cognitive benefits	1		
Factual knowledge	5	Flow	1	Working memory span	1		
Conceptual/Content knowledge	3	Helpfulness	1	EEG cognitive metrics			
Application	3	Learning beliefs	2				
Spatial knowledge	1	Engagement	3				
Comprehension	8						

Table 2.5: Overview of the coded articles with evidence of the design and pedagogical principles in VR

Cognitive processing	**Principle**	**S/N**	**Author**	**Year**	**N**	**Aims/Objectives of study**	**Methodologies**	**Results (*Effect Size d*; η^2)**	**Conclusion**
	Redundancy	1	Moreno & Mayer Exp 2	2004	75	Test the hypothesis of method affect learning	12(narration +text); 10(narration only); Lab; 2-way ANOVA	Retention: 0.19 Transfer: 0.18	No redundancy effect on retention, transfer No significant difference between both groups
Reduce extraneous processing		2	Makransky et al.	2019	52	Investigate whether the principles of redundancy learning generalize to VR	28(text condition); 24(text +narration condition); Lab; 2*2 mixed design.	Knowledge: -0.51 Transfer: -0.16	No redundancy effect on transfer and marginal significance on knowledge scores
		3	Liu et al.	2015	120	Investigated the redundancy effect in a virtual classroom when presenting multiple formats of instruction	40(audio-A); 40(audio + visual-AV); 40(visual-V); Classroom; ANOVA	Retention A vs AV): 0.57 Retention (V vs AV): 0.52 Comprehension (A vs AV): 0.54; V vs AV: 0.57	the simultaneous presentation of written text and narration resulted in better performance than learning with written or narrated text only.
		4	Liu et al.	2021	104	Examined the redundancy effect in a VR classroom	26 students in each group; Classroom; 2*2 ANOVA	Retention: 0.54; 0.09 Performance Efficiency: 0.52, 0.06*	Students who learned with redundant material performed better in retention and performance efficiency than those that did not.
		5	Baceviciute	2021	73	Explores whether redundancy design principles translate to VR	23(audio), 24(written), 24(redundant); Lab; ANOVA, post-hoc t tests	Redundant vs Auditory Retention: 1.04, 0.12* Transfer: 0.25, 0.02* Redundant vs Written Retention: 0.08 Transfer: 0.2	Some evidence of the redundancy principle to facilitate learning in VR.
	Redundancy Studies	6						**Median d = 0.20**	**Small and positive reverse-redundancy effect on learning**
	Signaling	7	Nelson et al.	2014	193	Examined the effect of visual signaling techniques of science inquiry in VR	98(visual signaling); 95(no visual signaling); Lab; ANOVA	Performance Efficiency: 0.49	Visual signaling increased efficiency of performance scores.
		8	Ahmad & Yahaya	2015	38	Investigated the design of VR environments with signaling principle to influence learning	18 students in each group; Classroom; pre-post ANOVA	Retention: 0.25 Transfer: 0.49	Signaling helped students recall and transfer better than no signaling in VR
	Signaling	9	Nelson et al.	2016	50	Examined the use of visual signaling to increase learning efficiency	Low-search signaling (11); low search -no signaling (14); high search signaling (9); low search signaling (16); Lab; 2*2 ANOVA	Performance efficiency: **	No evidence for visual signaling effect on learning in VR
		10	Yahaya & Ahmad	2017	130	Examined the effect of signaling principle in VR with different spatial ability	67(signaling), 63(no signaling); Classroom; ANOVA	Transfer: 0.71	Signaling improved transfer or learning in VR

		S/N	Author	Year	N	Aims/Objectives of study	Methodologies	Results (*Effect Size d*; η^2)	Conclusion
		12	Hwang & Shin	2018	100	Examined the effect of cueing on learning performance	50 students in each group; Lab; t test	Recall: **	No evidence of cueing on recall performance in VR
		13	Shin & Park	2019	32	Examine the effects of adding visual cues to increases the effectives of instructional animations in a procedural manipulative VR task	16 students in each group; Lab; MANOVA, t-test	Recall: **	No evidence of cueing on recall performance in VR
	Signaling-*Annotations effect*	14	Albus et al.	2021	103	Investigated whether annotation signals increase learning outcomes	56(annotations); 51(no annotations); Classroom ANCOVA	Recall: 0.26, 0.04* Comprehension** Transfer: 0.19, 0.03*	Some evidence of the effect of annotations in facilitating learning (Annotations improved recall and transfer, but not comprehension).
	Signaling-*Annotations effect*	15	Vogt et al.	2021	61	Investigated the effect of annotations and its interaction with intrinsic motivation in VR	28(annotations); 33(no-annotations); Lab; MANOVA, Regression	Knowledge: 0.24; 0.04* Comprehension** Application: **	Annotations improved knowledge scores in VR, but not comprehension and knowledge application.
	Signaling studies	16						**Median d: 0.41**	**Positive effect of signaling on learning**
	Scaffolding-Guidance	17	Moreno & Mayer Exp 2	2004	105	Examined student learning in a geographical VR simulation when supported with forms of scaffolds	28(pictorial aids); 25(no aids); Lab; 2*2 ANOVA	Pictorial vs No Pictorial Accuracy: 0.41, 0.05*	Pictorial scaffolding helped students learn more accurately in VR
		18	Moreno & Mayer Exp 2	2004	73	Examined the use of pictorial guidance scaffolds in VR geographical simulation	38(scaffolds); 35(no scaffold); Lab; 2*2 ANOVA	Accuracy: 0.75; 0.15* Transfer: 0.85; 0.19*	Scaffolds- pictorial guidance helped students transfer and learn more accurately in VR
		19	Nelson	2007	287	Examined the use of individualized, reflective guidance in a VR	Lab; Multi-level regression	Conceptual knowledge **	No guidance effect on learning
	Scaffolding-Guidance	20	Chen & Ismail	2008	184	Examined the effect of guided exploration in VR	62(Guidance); 58(No-guidance); Lab; multi-group pre-post	Learning gain: 0.96	Evidence for guidance effect on learning in VR
		21	Baydas et al	2015	146	Investigated the effects of guided 3D VR on learning on student retention	49(guided); 67(unguided); Lab; MANCOVA	Retention: -0.61; 0.10*	Guidance led to lower retention scores in VR.
		22	Ullah et al.	2016	57	Investigated the influence of procedural cognitive guidance on VR learning in chemistry	19 students in each group; Classroom; ANOVA	Performance Efficiency: 0.3	Guidance reduced number of errors, therefore increasing learning performance efficiency
		23	Topu & Goktas	2019	104	Examined the learning achievement of students with or without avatar-based guidance	45(guidance); 59(non-guidance); Lab; MANOVA, Pearson Correlation	Learning performance 0.4	No evidence of guidance on learning

	Principle	**S/N**	**Author**	**Year**	**N**	**Aims/Objectives of study**	**Methodologies**	**Results (*Effect Size d*; η^2)**	**Conclusion**
	Scaffolding-Navigation	24	Burigat & Chittaro	2016	53	Examine the influence of VR design factors-navigational aids on learner's acquisition	17(active navigation); 18(no navigation); Lab; Kruskal-Willi's test	Comprehension: 0.87	Navigational aids increased learners' comprehension in VR
	Scaffolding Studies	25						**Median d = 0.48**	**Medium and positive effect of scaffolding in VR (scaffolding enhances learning)**
Manage essential processing	Modality	26	Moreno & Mayer Exp 1	2004	89	Investigate whether method affects learning	13(narration); 14(text); Lab Two-way ANOVA design	Retention: 0.79 Transfer:1.23	Students remember more, achieve better transfer when using speech rather than onscreen text regardless of delivery medium
		27	Moreno & Mayer Exp 2	2004	85	Test the hypothesis of method affect learning	12(narration); 11(text); Lab; 2-way ANOVA	Retention: 0.89; 0.14* Transfer: 0.93; 0.46*	Learning with animation and narration is more efficient than learning with animation and text
		28	Erlandson et al.	2010	78	Examined the influence of communication modality on science inquiry learning in VR	39(audio); 39(text-based) Lab; pre-post ANOVA	Conceptual Knowledge** Procedural Knowledge**	No evidence of modality on learning in VR
		29	Do & Moreland	2014	175	Examined the influence of 3D multimodal on recall	Lab; ANOVA counterbalancing	Learning accuracy: -0.39	Students learned in visual than auditory condition
	Modality Studies	30						**Median d = 0.50**	**Medium and positive effect of modality on learning (modality enhances learning)**
	Pre-training	31	Meyer et al	2019	118	Investigated the effect of pre-training when learning through IVR	29(pre-train); 31(no-pretrain); Classroom; one-way ANOVA	Retention: 0.81 Transfer: 0.62	Pre-training helped students to learn better in retention and transfer knowledge scores.
		32	Petersen et al	2020	102	Examined the effects of pre-training on student learning on climate change	50(pre-train); 52(no pre-train); Lab- ANOVA pre-post	Declarative knowledge** Transfer: 0.46	Pre-training helped student transfer better, but not in declarative knowledge (some evidence of pre-training principle in VR)
		33	Howard & Lee Exp 2	2020	101	Applies attentional advice pre-training interventions to counteract the effect of distractions in VR	49(pre-training); 50(control); Lab; ANOVA	Retention: 0.58	Pre-training improved retention scores in VR
	Pre-training studies	34						**Median d = 0.59**	**Medium and positive effect of pre-training on learning**
	Sequencing	35	Vogt et al	2021	81	Examined whether animation or auditory text should be presented first in a VR lesson	22(animation); 19(auditory); Lab; MANCOVA	Knowledge: 0.67, 0.11* Comprehension: 0.30,0.03* Application: 0.26, 0.03*	Evidence of the sequencing on knowledge, but not on comprehension and application
	Segmenting	36	Parong & Mayer	2018	55	Investigate segmenting effect of immersive virtual reality vs	27(VR); 28(slideshow): ANOVA	Factual questions: 1.12 Conceptual questions:0.08	Learning with continuous lessons not under learner control, rather than

						a desktop slideshow for teaching scientific knowledge		Total test score: 0.92	short segments and under learner control hinders learning.
Fostering generative processing	Personalization	37	Moreno & Mayer	2004	48	Investigates the effect of *personalization* in virtual environment	12(personalized group); 12(non-personalized group); Lab; ANOVA	Retention: 0.77 Transfer: 1.64 difficulty: 0.67	personalizing instructional materials in a VR environment leads to improved learning outcome
	Imaging	38	Petersen et al.	2021	162	Examine the image principle in VR	ANOVA	Factual Knowledge: -0.47, 0.07*	Presence of pedagogical image led to lower learning
	Embodiment	39	Liew et al.	2016	107	Investigate the effect of smiling and talking rather than static pedagogical agents	53(static agents); 54(smiling agents); Lab; t test	Post-test: 0.19	Learning outcomes was not influenced by display expression of virtual agents
	Embodiment	40	Makransky et al.	2019	66	Examined whether the learning effects of pedagogical agents that matched the gender of participants	17 boys, 16 girls (female agent); 16 boys, 17 girls (male agent); Classroom; 2*2 ANOVA	Learning performance: 0.96 Knowledge: 0.67 Transfer: 0.93	Girls learned more with a female agent than boys (evidence of embodiment effect on learning)
	Embodiment	41	Petersen et al.	2021	162	Examine the embodiment principle in VR	ANOVA	Factual Knowledge: -0.37, 0.04*	High embodied agents led to lower learning
	Embodiment studies	42						**Median d = 0.22**	**Small and positive effect of embodiment on learning**
	Collaborative	43	Cho & Lim	2017	101	Examines the impact of collaborative learning on application, comprehension as compared to teacher-directed instruction	31 (collaborative problem solving-CPS); 31(collaborative observation-CO); 34(teacher instruction-TO); Classroom; repeated measures ANOVA	Comprehension CPS vs TD: -0.31; delayed test: 0.18 CO vs TD: 0.34; delayed test = 0.14 Application CPS vs TD: 0.36; delayed test: -0.11 CO vs TD: 0.84; delayed test: 0.63	Collaborative learning had higher learning than teacher-directed individual learning.
			Tseng et al	2020	96	Examines the effects of learning either individually or collaboratively in a VR	24 students each group; Classroom; ANOVA mixed model	Retention: 0.49 Delayed test: 0.70	Collaborative or pair work in VR led to increased learning
	Collaborative studies	44						**Median d: 0.43**	**Positive effect of collaborative learning in VR (collaborative enhances learning)**
	Immersion	45	Moreno & Mayer Exp 1	2004	89	Examine whether students learn better in IVR than conventional media	27(high immersion VR); 34(low immersion VR; Lab; 2*2 ANOVA	Retention** Transfer**	Immersion did not increase or reduce learning. No evidence for the immersion principle
		46	Moreno & Mayer Exp 2	2004	75	Examine whether students learn better in IVR than conventional media	33(high immersion VR); 42(low immersion VR	Retention** Transfer: 0.28, 0.03*	No significant difference on immersion
		47	Moreno & Mayer	2004	48	Examine whether immersion promote learning	12 students in each group;	Retention: -0.73, 0.11* Transfer: -0.30, 0.03*	Immersion led to lower retention and transfer learning

		S/N	Author	Year	N	Aims/Objectives of study	Methodologies	Results (*Effect Size d*; η^2)	Conclusion
		48	Schrader & Bastien	2012	84	Examine how the design of VR affect learning outcomes	42 students in each group; Lab; ANOVA; Mediation	Retention: -1.08, 0.23* Comprehension: -1.06, 0.22* Near Transfer: -0.99, 0.20* Far Transfer: -0.88, 0.16*	Immersion led to lower learning outcomes in retention, comprehension, and transfer
	Immersion	49	Makransky & Lilleholt	2018	104	Examines how the level of immersion impact learning outcomes	Lab; Crossover-repeated measures	Perceived learning effectiveness: 0.26	No significant difference on immersion effect
	Immersion	50	Meyer et al	2019	118	Examines the immersion effect in VR	60(IVR); 58(video);	Retention: -0.60 Transfer: -0.44	Immersion led to lower retention and transfer scores
		51	Makransky et al	2019	105	Examine the effectiveness of immersive VR as a medium for delivering lab safety	33(IVR), 37(DVR);	Transfer: 0.19	Immersion led to higher transfer scores
		52	Klingenberg et al	2020	89	Examined the effects of media on learning	24(IVR); 22(DVR);	Retention** Transfer: 0.14, 0.02*	Immersion led to higher transfer
		53	Zhao et al.	2020	75	Examines the immersion principle in VR	45(IVR); 30(video)	Comprehension**	Immersion did not increase or decrease learning
		54	Makransky et al. Exp 1	2020	131	Examined the instructional effectiveness of using IVR versus video for teaching scientific knowledge	67(IVR); 64(video)	Declarative knowledge** Procedural knowledge: 0.15	Immersion did not significantly lead to learning outcomes
		55	Makransky et al. Exp 2	2020	165	Examined the instructional effectiveness of using IVR versus video for teaching scientific knowledge	42(IVR); 41(video)	Declarative knowledge: -0.23, 0.03* Procedural knowledge: -0.16, 0.01* Transfer**	Immersion led to reduced declarative knowledge
		56	Nie & Wu	2020	53	Investigate the immersion principle in VR	13 students in each group	Retention** Transfer: 0.77, 0.15*	Immersion led to increased transfer scores
		57	Parong & Mayer	2021	80	Examined whether students learn better in immersive VR than conventional media	20 students in each group	Retention: -0.14* Transfer: -0.41	Immersion led to lower learning outcomes
		58	Liu et al	2021		Examined the immersion effect	26 students in each group	Retention: -0.10	No significant difference for immersion on learning.
		59	Barnidge et al	2021	133	Examines whether learning in VR aid learning outcomes	21(VR); 26(video); Lab; MANCOVA	Recall: -0.32 Cognitive elaboration: 0.41	Immersion led to lower recall
	Immersion Studies	60						**Median d = -0.10**	**Evidence of immersion principle (Immersion did not enhance learning)**
	Summarizing (GA)	61	Parong & Mayer	2018	57	examine the efficacy of adding a generative learning strategy to a VR lesson	28(summary group); 27(non-summary group); Lab; ANCOVA	Factual questions:1.14 Total test score: 1.12	Adding a generative learning strategy to a VR lesson significantly improves learning.

	Summarizing	62	Zhao et al.	2020	75	Examined the potential effects of using summarizing strategy in VR	22(summarizing); 23(non-summarizing); Lab; 2*2 ANOVA design	Comprehension: 0.15	Negligible effect of summarizing on learning
	Summarizing studies	63						**Median d: 0.56**	**Positive and medium effect of summarizing on learning (summarizing improved learning)**
	Learning by teaching (GA)	64	Fiorella et al.	2019	75	Examined the cognitive consequences of implementing learning by teaching in VR	28(learning by teaching); 30(control; Classroom; ANCOVA	Acquisition: 0.28 Application: 0.22 Organization: 0.11	Negligible effects of learning by teaching on learning outcomes
		65	Klingenberg et al.	2020	89	Examined the efficacy of using a GLS in VR	23(learning by teaching); 24(no learning by teaching); Classroom; one-way ANOVA	Retention: 0.6 Transfer: 1.26	Learning by teaching improved retention and transfer in VE
	Learning by teaching studies	66						**Median d: 0.57**	**Positive and medium effect of learning by teaching on learning (learning by teaching improved learning)**
	Practice testing	67	Parong & Mayer	2021	61	Determined whether the effect of practice testing can be extended to VR lessons	15 students in each group; Classroom; ANCOVA	Retention: 0.34 Transfer: 0.57	Practice testing improved retention and transfer scores in VR
		68	Parong & Mayer	2021	80	Examined the effect of practice testing in VR	20 students in each group; Lab; ANCOVA; Mediation analysis	Retention: 0.39; 0.04* Transfer: 0.10	Practice testing improved retention scores in VR, but negligible effects on transfer
	Practice testing studies	69						**Median d: 0.35**	**Small and positive effect of practice testing in VR**
	Prompting	70	Vogt et al.	2021	81	Examines whether prompting enhances differentiated levels of learning	20(elaboration prompt); 22(no prompt); Lab; ANOVA	Knowledge** Comprehension** Application: 0.53	Elaboration prompt helped on higher level outcomes- Application
		71	Vogt et al.	2021	67	Investigates the effects of prompting on learning outcomes in VR	31(elaboration prompt); 33 (no prompt); Lab; MANOVA	Knowledge: 0.41 Comprehension** Application**	Evidence of prompting effect on knowledge.
	Prompting studies	72						**Median d: 0.47**	**Positive and medium effect of prompting on learning in VR**
	Enactment	73	Makransky e al. Exp 2	2020	165	Examined the effect of adding enacting – a generative activity in VR	41(enactment); 42(without enactment); Classroom; ANCOVA	Declarative knowledge** Procedural knowledge: 0.78; 0.14* Transfer: 0.62; 0.09*	Enactment improved procedural knowledge and transfer
	Planning	74	Nie & Wu	2020	53	Investigates the effect of early planning on outcomes	14(planning); 13(without planning); Lab; 2*2 ANOVA	Retention** Transfer:0.77; 0.15*	Planning improved transfer learning in VR
	Generative activity studies	75						**Median: 0.57**	**Positive and medium effect of generative activities on learning**

Note: d is calculated Cohen effect size; * is eta-square(η^2) effect; ** is negligible effect i.e., d <0.10

CHAPTER 3

STUDY II: A CASE FOR THEORY-DRIVEN VIRTUAL REALITY RESEARCH IN ENGINEERING EDUCATION[2]

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[2] Oje A.V., Hunsu N., Dominik M. Submitted to Computers & Education: X Reality, July 23, 2022

3.1 Abstract

In recent years, Virtual Reality (VR) has gained popularity in education, particularly engineering education. However, review studies that enlighten engineering educators and instructional designers about the usage and deployment of VRs to enhance instruction and learning in engineering education are still scarce. This article argues that engineering education VR design decisions should be based on theory-informed studies. We assessed the state of VR research in engineering to determine how engineering VR studies are guided by theory-driven and evidence-based imperatives. 51 studies were included in the literature synthesis and analysis using a systematic approach to selection and screening. The results of this analysis reveal that numerous studies focused on usability outcomes. Several VR studies lacked a theoretical or pedagogical framework to study the design of VRs for engineering educational content. This article intends to inspire engineering educators and instructional designers to build VR research imperatives that incorporate design principles for effective VRs that draw on relevant cognitive and non-cognitive learning theories. This paper highlights the significance of these research directions for understanding the cognitive and socio-cognitive engagement mechanisms and positive learning benefits of VR applications in engineering education.

Keywords— Virtual Reality (VR), design principles, learning theories, pedagogical principles, engineering education.

3.2 Introduction

There has been an exponential increase in the use of Virtual Realities (VR) for instructional applications across several educational fields in recent years. For example, Makransky and Petersen (2021) showed in an analysis of recent literature that education VR research has increased dramatically over the last decade, and attributed this increase to a growing interest, adoption, application, and research of instructional VR technologies in educational literature. They conducted a search in the Scopus database and found that over 500 educational VR research studies were published 2016 and 2020 – a considerable proportion of which were peer-reviewed literature. These growing body of research studies has examined applications of instructional VR tools to address educational challenges such as the use of VR to motivate student to learn, enhance students cognitive and spatial abilities, among other relevant educational outcomes.

VR refers to systems or platforms that use computer graphics to simulate multiple sensory cues (visual, tactile, aural) and display a real-world perception in an artificial or virtual environment (Bailenson et al., 2008). Due to advances in computing and image processing capabilities, recent VR technologies can render real-world scenes in a manner that emulates near-real experience. VR technologies are categorized as immersive VR (IVR) and non-immersive desktop VR (DVR) based on the type of experience they afford. Immersive VR experiences are those that are fully integrated into the user's environment and necessitate the usage of head-mounted devices (HMD) such as Oculus Rift or HTC Vive. Since the use of HMDs completely immerses users in the experience, they provide the opportunity for a greater sense of 'being there'. On the other hand, desktop VR do not require the use of headsets – only computer keyboard and mouse devices are needed to interact with the virtual reality environment, which are projected on a desktop computer monitor or television screen. In addition, because users view and interact with desktop VR representations without being embedded in the environment themselves, they also do not get the same level of immersiveness that HMD devices offer.

VR technologies so far have remained prominently within the entertainment space. However, with VR developing and its cost falling, educational technology enthusiasts have proposed that adopting VR technologies can revolutionize pedagogy and learning. For example, heavy industrial equipment or less accessible environments like nuclear reactors or the Milky Way (for example) can be modeled in VR. Using VR, students can now experience and interact with such equipment and access those environments without setting foot outside the classroom. With the aid of VR, educators can offer many experiential learning opportunities that are otherwise costly, impractical, or even impossible to support without VRs. However, as we become more comfortable with VR technologies, the need to know how to harness their educational potential has also increased tremendously.

Within the last decade, multiple empirical studies that explore how VR is used in educational contexts have been published. Similarly, a few review studies focusing on the application of VR in K-12 and higher education settings have also been published (Jensen & Konradsen, 2018; Luo et al., 2021; Merchant et al., 2014; Mikropoulos & Natsis, 2011). Educational theories play a prominent role in identifying and understanding the factors that promote effective pedagogy and learning experiences. However, a cursory exploration of many existing empirical and review studies on educational VR reveals that very few educational VR designs and research studies emphasize grounding educational VR implementation in empirically tested cognitive and non-cognitive theories of learning and instruction. We want to take a step towards closing this gap.

In this article, we briefly highlight several applications of VR in STEM education, and the lack of theoretical pointers and guardrails in current engineering education VR research. We argue that engineering education can leverage on the affordances of educational VR. However, integration of VR in engineering education must be informed by educational theory and evidence-based imperatives. In Section 3.3, we describe the use of VR in several educational contexts. We also highlight some trends in current engineering education VR research. In Section 3.4, we argue for theory-based VR design in engineering education and highlight different relevant theoretical perspectives that designing and implementing effective VR in Section 3.5. Based on the theoretical perspectives highlighted in Section 3.5, we suggested potential directions for future VR research in engineering education.

3.3 Virtual Reality Applications in Educational Setting

Instructional technologies researchers have proposed several explanations on the increasing interest in, and adoption of VR applications for educational and instructional purposes (Alfalah, 2018; Marks & Thomas, 2022). Most notably, they claim that VR makes it possible to present educational contents in ways that partially or fully immerses the learner in the learning experience (Bowman & McMahan, 2007). Some have argued that such immersion engenders experiential learning experiences that foster better understanding of certain conceptual and procedural knowledge (Fromm et al., 2021; Kwon, 2019). Advocates argue that educational VR can allow learners to experience a variety of environments with diverse placements and perspectives. Consequently, educational VRs can facilitate discovery-based activities, stimulate learning interest and motivation (Pantelidis, 2010). Additionally, students can observe various phenomena and complete procedural tasks in controlled VR environments that mimic real life experiences.

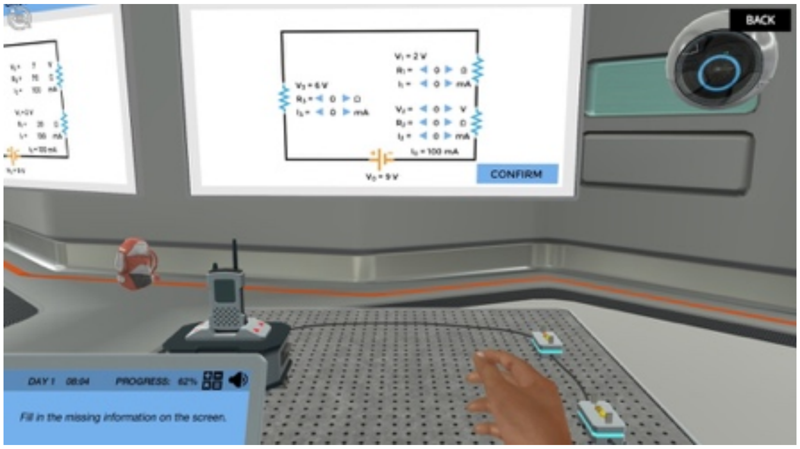
VR applications have revolutionized the way instructional contents can be delivered and experienced across several educational fields. For instance, students can experience and learn about near and distant places by exploring geographical scenes rendered in VR without leaving the classroom, sometimes even without leaving their own home. Unlike video representations of the same learning content, students can interact with the environment the experience in a more vivid way. Within the medical field, educators have leveraged VR technologies to deliver instructional contents, such as surgical procedures, human anatomy etc., in ways that are cost effective and improve students' learning experiences (Javaid & Haleem, 2020). Medical science educational fields have leveraged the use of instructional VR platforms to facilitate safe, near-real life medical experiments where students can learn procedural skills that are too risky or costly to support otherwise (Merchant et al., 2014). Jenson and Forsyth (2012) suggested that VR simulations have been used in nursing education to expose students to various medical situations, and students can repeatedly perform practical hands-on medical procedures or surgeries in simulated risk-free environments. Apart from their application in medical science and geography education, several studies have reported the benefits of VR activities in language learning (Lan, 2020), physics and astronomy (Barnett, 2005; Chen et al., 2007; Porter et al., 2020), mathematics (Hsu, 2020), psychology and other STEM (Science Technology Engineering Math) fields (Pellas et al., 2020; Riva, 2022).

Some studies have suggested that the kind of immersive learning experiences that instructional VR afford can remediate students' misconceptions of geographical and geological concepts (Yusuf & Safitri, 2021), and offer better visualization and spatial navigation of abstract concepts than traditional teaching methods could do (Bailenson et al., 2008; Salzman et al., 1999). Others have suggested that instructional VR technologies can facilitate collaborative exchange, which may reduce learning anxiety – for example, among foreign languages students (Zheng et al., 2017). They could also stimulate student's motivation and self-efficacy to complete procedural task science laboratory experiments (Makransky et al., 2019), and support emotional regulation strategies that relate to negative and positive emotions (Colombo et al., 2019).

3.3.1 Virtual Reality Application in Engineering Education

Engineering education is a practical and experiential field that integrates theory and practice from science through lectures, hands-on learning, simulation-based learning, and laboratory experiences. Considering this, laboratory instructions have always been an integral core of the undergraduate and graduate engineering curriculum and experiences (Feisel & Rosa, 2005). Instructional engineering laboratories provide students with an avenue to experience theory-to-practice of engineering concepts and afford hands-on platforms for students to develop the psychomotor, design, cognitive and procedural skills that are necessary for the professional formation of engineers (Feisel & Rosa, 2005; Nikolic et al., 2021). Despite the significance of practical laboratories to the engineering curriculum, the cost of setting up physical laboratories can be prohibitive. Not alone are some laboratories expensive to maintain, but time and space constraints may also limit the expansiveness of the laboratory experiences that some engineering programs can support. Apart from the constraints mentioned above, the academic disruptions caused by the COVID-19 pandemic demonstrated vividly the peculiar short-comings of our traditional brick-and-mortal laboratory. The onset of the COVID-19 many instructors to seriously consider alternative mechanisms for delivering and supporting engineering instructional laboratory experiences (Leung et al., 2020), without losing the educational value of the instructional laboratory experience. The situations noted above demonstrate the relevance of virtual laboratories or VR-based laboratories as platforms for supporting alternative laboratory experiences in engineering, not necessarily as a replacement for traditional laboratories but as an addition to the known curricula. Like in medical education, engineering education may leverage the affordances of VR technologies to facilitate the instruction of engineering knowledge, and to support the delivery of engineering laboratory contents (Abulrub et al., 2011; Pantelidis, 1997). Many students find certain abstract engineering concepts too intangible and cognitively challenging to grasp. Such students may struggle to formulate coherent mental models of such abstract engineering concepts and, consequently, fail to gain a conceptual understanding of such concepts (Streveler et al., 2008). Educational VR environments can be especially beneficial in supporting students learning of such content. For example, some students may find electromagnetism, or 3-D statics concepts, etc. difficult to imagine and grapple with because such concepts are unobservable in the physical world. However, such abstract concepts may become more vivid to students and aid their understanding and learning when they are simulated through Virtual Reality Learning Environments (VRLEs) (Manseur, 2005).

Over the years, research studies have described different uses of VR-based instructional applications in specific learning situations to aid conceptual understanding, problem-solving, and skill training, among others, in engineering learning contexts (Halabi, 2020; Stuchlíková et al., 2017). In the context of electrical engineering for instance, Salzman et al. (1999) opined that virtual reality's multisensory cues could improve learners' interaction with electrical engineering activities in a VRLE. To help students learn complex concepts and develop design skills, they developed a VR application to assist students with grasping challenging electric fields and electrostatics concepts (Salzman et al., 1999). They observed that students gained better conceptual understanding of the distribution of forces in an electric field as they interact with concepts and navigate multiple perspectives in a VRLE. Valdez et al. (2014) designed and used a prototype VRLE called the Virtual Electric Manual (VEMA) to teach and demonstrate various electrical experiments using the technology's visualization capabilities. VR-based instruction has been used to facilitate inductive learning of fluid pressure in fluid mechanics (Savadatti & Johnsen, 2017), fluid statics and dynamics (Johnsen & Savadatti, 2019), and Truss system (Banow & Maw, 2019) in mechanical engineering applications. Apart from their use in delivering engineering contents, some articles have described the use of VRLEs to facilitate problem-solving skills in craft production and manufacturing design processes (Aqlan et al., 2019), problem-solving and collaborative skills in an engineering statics domain (Tuttle et al., 2019). Figure 3.1 depicts screenshots of VRLEs of an engineering content.



Fill in the missing information on the screen.

Figure 3.1: VR simulation in conceptual and procedural learning of electric circuit concepts
Source: from labster

3.3.2 Virtual Reality in Engineering Laboratory and Training Application

The recent COVID-19 pandemic shutdown interrupted normal instructional practices and forced many colleges, and thus their laboratories, to explore online platforms (including VRLEs) to support alternative laboratory curriculum and instructions. Before the COVID era, however, providing access to physical laboratories to support large student cohorts was already challenging for some STEM programs. Administrative and logistic challenges with traditional laboratory offerings often stem from high procurement and maintenance costs, resource scalability (including managing limited operational time and inability to support students at-a-distance), inclement weather conditions among other (Pantelidis, 1997, 2010; Ritter & Chambers, 2019). However, practical, and real-time, laboratory exercises can be simulated in safe and controlled VR environments that mimic the experiences students get in physical laboratories. For instance, students can perform electric circuit analysis and learn electrical concepts in a desktop VR, just like they would in physical laboratories without the fear of damaging electrical equipment. Similarly, students may practice relatable hands-on mechanical engineering concepts and laboratory activities in an immersive VR environment, where they can safely handle virtual machines with little or no supervision.

VR platforms can support laboratory instructions and experiences in engineering fields because practical activities that result in the acquisition of procedural skills can be rendered in VRLE-based training systems (Kollöffel & de Jong, 2013). For instance, Singh et al. (2021) used a VRLE to train engineering students to 'handle' electronic hardware and conduct laboratory experiments. They reported that the students they observed found the virtual activities to be especially useful for learning. In addition to supporting procedural skill training, VRLEs can help with visualizing abstract ideas that are relevant to practical laboratories. For example, students can visualize signals generated by electronic hardware and manipulate virtual electrical hardware to gain better conceptual understanding of electrical engineering contents. Other examples of VLRE for engineering laboratories have been described in existing literature. For example, VRLEs had been developed, to illustrate relative motion concepts (Kozhevnikov et al., 2013), to train engineering students: in operating a transformer in an electrical power station (Barata et al., 2015); in chemical production plants operations (Ouyang et al., 2018); in operating weft-knitting machines (Zhang et al., 2018). Zhang and colleagues argued that VRLE fostered operational skills, practice ability, and holistic knowledge of weft-knitting engineering in their participants.

3.3.3 The state of VRLE Research in Engineering Education

Considering the growing recognition of the potential of educational VR to support the instruction and learning of conceptual knowledge and procedural skills across engineering fields, there has been a proliferation of published studies that focused on the use of VRLEs to facilitate engineering education in both peer-reviewed and non-peer-reviewed research literature. In a recent effort we conducted a literature search using "Virtual Reality" AND "Engineering" AND "Education" OR "training" OR "learning" OR "teaching" in the Web of Science, Wiley, EBSCO Complete, and IEEE Xplore databases, to explore the expanse of the virtual reality research in engineering education within the last decade (2011-2021). We identified 1492 VR studies that were reported in English language. Title and abstracts filtering were conducted to eliminate irrelevant and non-empirical VR research literature to identify VR-focused empirical studies only. Overall, 51 studies that reported empirical observations of VRLEs in engineering learning contexts were identified. Different study features were coded and explored using the visualization capabilities of R studio 2021.09.02 to identify trends in VR research in engineering education.

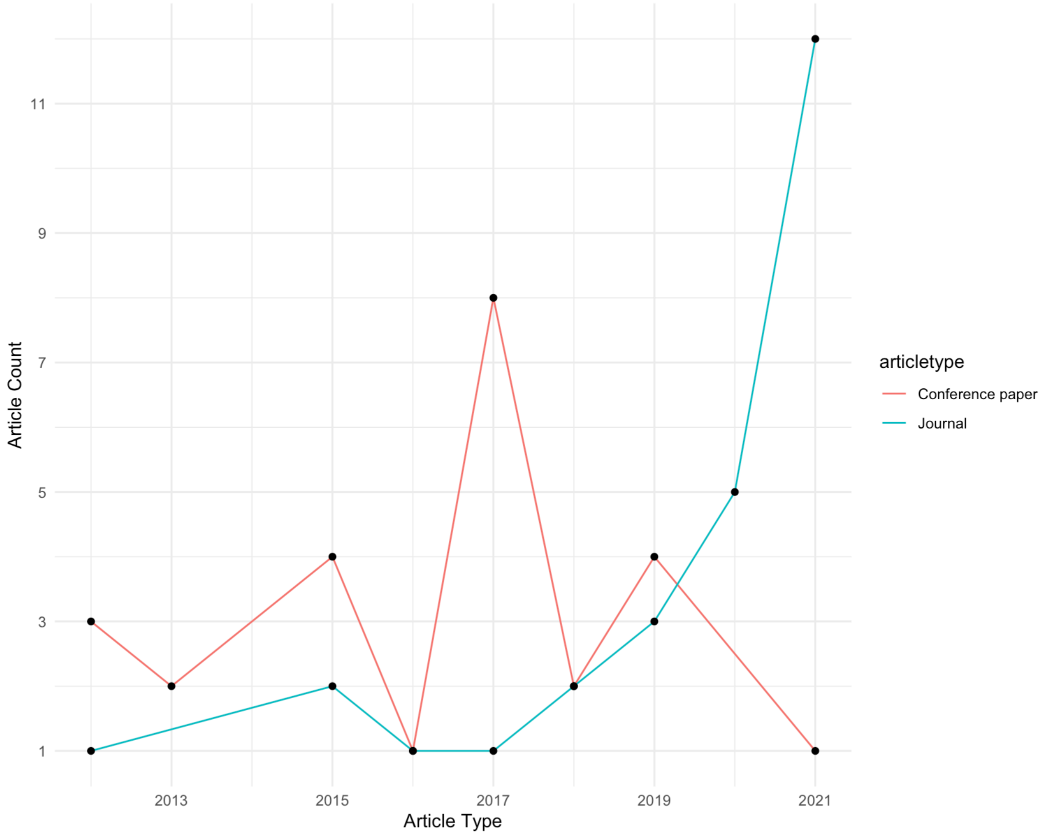


Figure 3.2: The growth of VR in engineering education

Figure 2 shows VR-focused studies in engineering education contexts have increased steadily within the last 5 years – 49% of all VR studies were published between 2019 and 2021. Next, we explored how these studies used empirically tested theories and which our outcomes were typically measured based on referent theory. Figure 3 showed that 21% of the studies found integrated theory both in supporting their study conception and interpretation, 15% referred to some theory or theoretical frameworks superficially. The major (63%) of engineering education VR studies made no reference to or use of theoretical or pedagogical frameworks. Lastly, we examined the learning outcomes that were assessed in the studies that observed were identified. Most of the studies observed ($N = 17$) assessed participants' perception of *usability* of VR-based instruction or a VRLE. Nine studies assessed *cognitive outcomes* such as retention, comprehension, knowledge transfer, or problem solving. We categorized learning outcomes that examined affects, motivation, spatial ability, cognitive overload as *others*.

Recently, there has been noticeable increment in the number of published articles that promote the relevance of VR to engineering education, and thus its adoption in fostering experiential learning of certain engineering contents. Upon a closer scrutiny however, we observed that the efficacy claims of many of these studies are founded upon sparse, or no strong theoretical or pedagogical framework. These observations prompted us to carefully explore extant multi-media learning, and educational VR literature to identify theoretical frameworks that might be germane to technical and pedagogical considerations for designing effective instructional VR. Consequently, we made the case for more theory-driven design and studies of VRLEs for engineering contents in the next section. We followed-up on our arguments by suggesting specific relevant theories in Section 4.

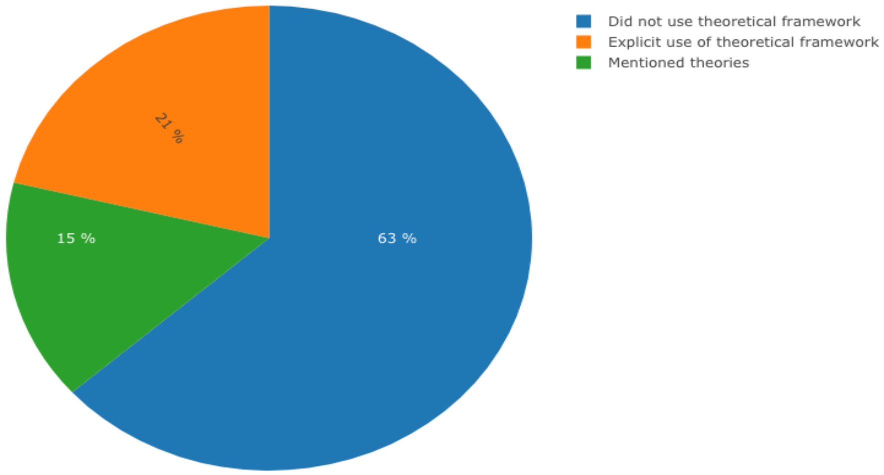


Figure 3.3: The Integration of Theoretical or Pedagogical Framework in VR research

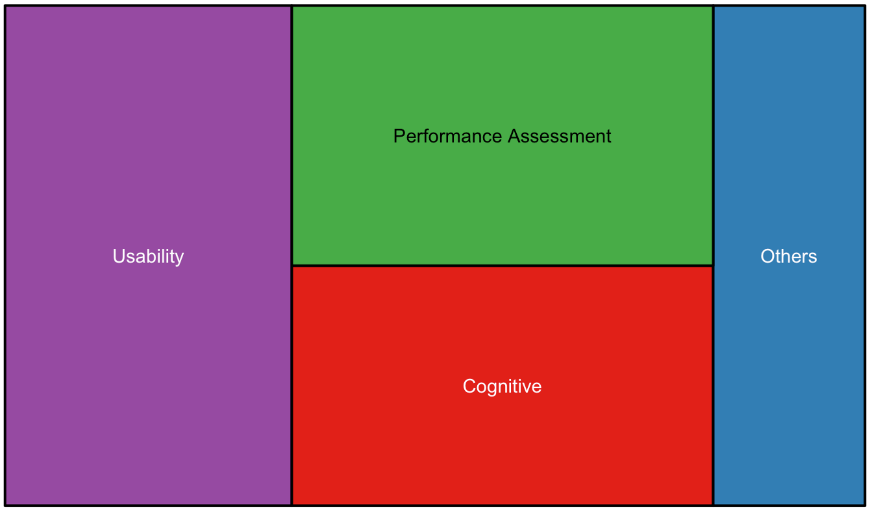


Figure 3.4: A tree map showing the category of learning outcomes

3.4 The Case for Engineering Education VRLE Design and Research Grounded In Multimedia Learning Theories And Principles

In sections 3.3, we highlighted different applications of instructional VR in some STEM learning contexts, including in engineering education. We also highlighted that some have proposed several arguments to call for VRLE-facilitated STEM education. Some researchers argue that VRLEs can foster conceptual and procedural knowledge (Singh et al., 2021), engender learning interest, and promote student engagement (Huang et al., 2021; Quishpe-Armas et al., 2015). Others claim that VR-based instruction may also facilitate non-cognitive skills such as collaborative strategies and teamwork engagement (Huang, 2018; Nelson & Ahn, 2018; Stuchlíková et al., 2017; Syed et al., 2017). As the cost of developing and acquiring educational VR technologies for instruction and learning in classroom reduces, one would expect that instructional VR aids will become more readily available for classroom instruction. Hence, engineering educators and curriculum developers might need to begin to actively consider ways to leverage the potential educational affordances of VR for facilitating the instruction and learning of engineering context to which they most appropriate.

Although there have been many positive claims about the instructional value of VRLEs, many of these claims are based on conjectures, student self-reports, or even anecdotes. Some claims are based on thinly supported empirical evidence, which in many cases was not grounded in any well-established cognitive and multi-media learning theories. Some researchers have even expressed their concern about the dearth of theoretical and methodological rigor in extant educational VR studies. They argue that we may be less able to optimize VRLEs to support effective learning and instruction if we are unable to propose, explain, or predict the effect of instructional VR on learning engagements and outcomes (Hamilton et al., 2021; Mikropoulos & Natsis, 2011; Radianti et al., 2020). Arguments for, or against, the effectiveness of VRLEs as instructional aids must have strong theoretical and empirical supports. However, prevailing trend (Section 3.3) suggests that engineering-focused VR studies sparingly draw upon pedagogical and theoretical framework. Despite the potential benefits that instructional VR might have on revolutionizing how some engineering contents can be delivered, VRLE designs and pedagogies that are not based on evidence-based principles may actually distract from learning – which would defeat the objective for adopting them as instructional supports in engineering education. As interest in exploring and adopting VR for instructional purposes increases, so must theory-informed and data-driven design and research of instructional VR.

The capabilities of emerging VR technologies to support cognitive, embodied, and experiential learning experiences and to promote the acquisition of conceptual and procedural knowledge in engineering education are increasing exponentially. As such, it is unthinkable that stakeholders of engineering education will slack in leveraging the educational affordances of VR to facilitate student learning experiences in engineering classrooms and laboratory instruction. As suggested earlier, the design, development, and adoption of VR technologies for engineering instruction must rely on evidence-based theoretical principles (Kalyuga et al., 1999, 2000; Mayer & Johnson, 2010; Pollock et al., 2002). Unfortunately, very few empirical studies of VRLEs of engineering contents have drawn on educational and psychological theories to investigate the cognitive and socio-cognitive creation of knowledge within instructional-VR ecosystems. Rather, the emphasis of many prior VR studies had centered on the aesthetic designs and capabilities of the different technological features of instructional VR, or on students' perception of VR usability, affects and emotions. However, emotional appeals do not necessarily translate to qualitative learning experiences. Rather, educational psychologists and instructional theoreticians strongly recommend balancing the emotional benefits of the 'interesting features' of multi-media learning environments and their cognitive consequences (Sundararajan & Adesope, 2020).

As such, we argue that more theory-driven studies that investigate imperatives for designing effective VRLEs for engineering contents are needed. Apart from investigating VRLE design considerations, studies that explore students' behavioral, cognitive, and social engagement as they learn engineering contents in VRLEs, as well as how to facilitate meaningful learning and instruction in VRs are urgently needed. Such empirical studies are important for identifying evidence-based recommendations for designing and implementing efficacious educational VRLEs for engineering learning contexts. In fact, for adoptions of VR for any engineering instruction to be ethnical, such adoption must "first, do no harm." – because poorly designed and implemented instructional VR could be deleterious to learning (Parong & Mayer, 2018). Some theories that are relevant to effective instructional VR design and implementation, and research are briefly discussed in the next section.

3.5 Theoretical Perspectives on the Educational Affordances of Instructional Multimedia and VRLEs

Developers and promoters of instructional VR argue that the aesthetics of VRLEs design promotes arousal and immersion. The arousal hypothesis holds that the attractive graphics or auditory design of VRLEs promote a sense of *immersion* that make VR learning experience enjoyable (because VRs engender positive emotions and learning engagement). They also suggest that the perceptual realism of VRLEs could induce *flow* or *presenc*e, which can stimulate positive emotional response and willingness to engage in VR-based learning content (Parong & Mayer, 2021). While the arousal and immersion hypotheses may seem rational, emotional, and affective arousals also may be insufficient to ensure meaningful learning engagement within VRLEs. Similarly, aroused interest or emotional responses may not necessarily translate to positive learning outcomes (Mayer, 2020). In fact, emotional arousals may distract from learning and in some situations (Makransky et al., 2019). Critics have argued that *seductive details,* such as excessive imagery and background sounds (in VRs for example) can engender *extraneous cognitive processing* that may inhibit learning (Moreno & Mayer, 2000; Sundararajan & Adesope, 2020; Sung & Mayer, 2012).

Rather than relying on VR imageries and features only to promote learning engagement and outcomes through the arousal of achievement emotions, VRLE design for engineering contents can be informed by intentional applications of design principles that are grounded upon cognitive and non-cognitive theories of learning that have strong empirical supports. Such intentional research and development initiatives may draw on existing multi-media learning design principles. In this section, we highlight cognitive and non-cognitive theories that may be relevant to advancing VRLE designs and pedagogy research in engineering education.

3.5.1 Design-focused cognitive principles for VRLEs

Cognitive Load Theory (CLT)

Building on the tenets of CTML, the CTL proposes that human limited memory capacity can be overloaded (Sweller et al., 1998), especially when the information being processed is novel (Sweller et al., 2019). According to the CLT, instructional information may be categorized into three kinds of cognitive loads that are processed in working memory – intrinsic, extraneous, and germane cognitive loads (Sweller, 2005a). Section 2.3.1.1 provides a comprehensive overview of the CLT theoretical framework.

Cognitive Theory of Multimedia Learning (CTML)

The CTML was proposed by Richard Mayer and colleagues to explain and predict how learning ensues in multimedia learning environments. In Section 2.3.1.1, the CTML theoretical framework is described in detail. In summary, CTML proposes that multi-media information processing occurs through two distinct processing (visual and verbal) channels. Further, CTML presumes that working memory capacity is limited – meaning that learners can only process a limited amount of information per time. Lastly, the CTML presumes that meaningful learning occurs in multimedia environments when learners are actively engaged in optimal cognitive processing (Mayer & Moreno, 2002).

To be meaningful engaged with learning in multi-media learning environments, learners must intentionally select the most relevant information, and organize selected information to build a coherent mental representation of the instructional elements being processed (Albus et al., 2021). The cognitive processes of selecting and organizing important instructional material is particularly critical to educational VRLEs because the extensive sensory inputs from VR environments has the potential to overwhelm learners' cognitive capacity and negatively impact learning.

Relevance of CTML and CLT for VRLE design

Theorists have proposed and tested several principles for designing multi-media learning platforms based on the propositions of the CTML and CLT. In VRLEs educational content are delivered in combination of aural (spoken words), textual (written words), or animations modes (Albus et al., 2021; Parong & Mayer, 2018). Visual contents in VRLEs may contain dynamic or static animation accompanied by narration, or simulated action accompanied by written and spoken information sources. Typically, CTML principles are suited to explaining the cognitive processes involved in learning from multimedia environments.

For example, *redundancy principle* of multi-media suggests that "redundant material interferes with rather than facilitates learning" because both the auditory and visual processing channels can be overloaded (Sweller, 2005b). Meanwhile, the *modality principle* suggests that "low-experience learners more successfully understand information that uses narration rather than on-screen text" (Oberfoell & Correia, 2016). Drawing on these two principles, VRLEs design must consider how best to represent different instructional information in ways that reduce the potential for cognitive overload in most learners (*redundancy principle*), while balancing texts and narratives for certain learner groups (*modality principle*).

The *coherence principle* of multi-media learning design proposes that learning improves when interesting but irrelevant words, pictures, symbols sounds, music, or animations inhibit learning (Moreno & Mayer, 2000). Although the presence of these so-called *seductive details* might pique students' interest and arouse affects and emotions, they may also increase the extraneous cognitive load and impede learning (Moreno & Mayer, 2000; Sundararajan & Adesope, 2020; Sweller, 2020). Drawing on CTL therefore, the coherence principle of multimedia learning design emphasizes that extraneous instructional information in multi-media learning should be minimal. Irrelevant details (also referred to as seductive details) have been repeatedly shown to inhibit learning (Mayer, 2017; Mayer, 2020; Sundararajan & Adesope, 2020). Mayer argues that poorly designed multimedia instructions engender extraneous processing (Mayer, 2017). As such, the coherence principle suggests that the design philosophy of VRLE must be to minimize details that may endanger extraneous cognitive processing, even if VRLE developers think such details might arouse interests and emotion (Mayer, 2009).

The *pre-training principle* of multi-media learning proposes that learners are better primed to process a multimedia message more deeply when they are familiarized with key-terms and basic concepts or characteristics prior to engaging in the main learning activity (Mayer, 2017). Prior experimental studies have concluded that pre-training exposures can increase recall, comprehension, and knowledge transfer (Meyer et al., 2019; Parong & Mayer, 2018). VR environment can be cognitively intensive for students with limited prior exposure or experience in a similar environment. In the same vein, the segmentation principle of multi-media learning could be relevant for the designs of VRLEs. The principle proposes that "people learn better when a multimedia message is presented in user-paced segments rather than as a continuous unit when information is presented in segments, rather than one long continuous stream" (Mayer, 2009). Parong and Mayer (2018) found that learners who received VR multimedia lessons in short segments performed better on factual questions than those in a VR control group. Their findings demonstrated the segmenting principle's applicability in VRLE designs.

Relevance of non-cognitive multi-media theories to VRLE design

The cognitive theories discussed so far, and the principles that stem from them do offer insight into relevant considerations that could guide VRLE design philosophies. They may also explain the effects of educational multimedia technology platforms on cognitive learning outcomes. However, because the engineering profession is practiced in highly collaborative contexts, it is essential that future VRLEs research and development should draw on extant socio-cognitive theories, and theories of social engagements in learning contexts. Some prior studies have indicated the effect psychological and emotional factors (such as achievement emotions, presence, interests, self-beliefs, etc.) significantly have direct or indirect effects on learning engagements, cognitive learning processes, and cognitive learning outcomes (Mayer & Estrella, 2014). For instance, VRLEs have been suggested to trigger situational interests, presence, and flow; these psychological factors affect multi-media and VR learning experiences. Multi-media learning theorists have proposed the Cognitive-Affective Theory of Multimedia Learning – CATML (Moreno & Mayer, 2007) to accommodate the role of affective and psychological factors on multi-media and VR learning experiences. Also, the Cognitive-Affective Model of Immersive Learning- CAMIL (Makransky & Petersen, 2021) frameworks describe how cognitive, affective, and psychological interaction and factors influence learning processes and outcomes in multi-media and VR learning environments.

3.5.2 Pedagogy-focused principles for VRLE implementation

Design philosophies that are informed by empirically tested principles are pertinent to the research and development of effective VRLEs for supporting learning and instruction in engineering education. However, the quality of students cognitive and socio-cognitive engagement in any learning environment is equally critical to achievement. Learning is a generative activity that is contingent upon how learners interact with instructional content – i.e., learning depends on the quality of the cognitive activities that students engage in the learning process (Fiorella & Mayer, 2016). Even when VRLEs are well-designed, some learners may be unable to get meaningful learning experiences in VR environments. As such, it is important for research and development initiatives of VRLEs for engineering contents to explore how students interact with instructional material in VRLEs, and how to encourage students to use appropriate learning strategies while learning in VRLEs. Subsequently, we will briefly highlight learner-focused theoretical frameworks and principles that may be relevant in facilitating learning engagement in VRLEs.

Generative Learning Principles (GLP)

The GLP framework suggests that learning is not a passive recipience of information. Rather, learning occurs when learners employ learning strategies that foster meaningful cognitive engagement and active processing of instructional content or information (Mayer, 2020). Theorists propose that participating in generative learning activities enhances cognitive processing and ensures meaningful learning (Fiorella & Mayer, 2015; Mayer, 2005; Wittrock, 1974). When learners engage in generative learning activities, they actively select, organize, and integrate (SOI) instructional materials in ways that enhance cognitive processing and a deeper understanding of the instructional material. Engaging in generative learning activities prime learner to identify and select the most important content of the instructional material (e.g., by paying attention to the most relevant words or graphics). Generative activities gear the learner to organize and form a coherent mental representation of the relevant information they select. Lastly, the learner integrates the new mental models that are generated from their cognitive processing with prior knowledge already stored in their long-term memory (Fiorella & Mayer, 2015, 2016).

Typically, many students lack the skill or the impetus to engage in metacognitive and self-regulatory activities that could enable them to take ownership of their own learning (Carpenter & Pease, 2013). In fact, novices often lack the strategy to isolate relevant information from irrelevant ones during the learning process (Johnson-Glenberg, 2018). Hence, a typical student might focus more on the aesthetic and exciting features of a VR environment if some pedagogical pointers or prompt to strategic engagement are not provided. In CTML terms, the aesthetics, imagery, and design features of VR environments could constitute *seductive details* that engender extraneous cognitive processing and result in a cognitive overload. However, infusing generative learning activities into VR-based learning could foster germane cognitive processing that enhances the learning experience and outcome. As such, the pedagogy of VR-based learning should integrate generative learning activities that intentionally direct students to focus more on relevant details of VRLE content that are germane learning the material and creating knowledge of engineering contents. Several generative learning strategies have been identified in the literature (Fiorella & Mayer, 2015, 2016). However, we highlight three generative learning strategies (the use of *self-explanation, summarizing* and *elaboration*s) that can facilitate meaningful learning engagement in a VRLE.

Self-explanation: involves students' explaining the to-be-learned concepts to themselves (Wylie & Chi, 2014). For example, students may be asked to think aloud as they interact with VRLE knowledge contents – particularly with the goal to help them identify relevant knowledge details and organize their thoughts, and to elicit misconceptions they might have about the material. Self-explaining could help learners to elaborate on main ideas (Bisra et al., 2018), generate inferences, and link them with their prior knowledge (Fiorella & Mayer, 2016; Roy & Chi, 2005; Wylie & Chi, 2014). The report of some studies suggests that self-explanation enhances problem-solving skills (Kwon et al., 2011) and fosters students' self-efficacy (Crippen & Earl, 2007). Self-explanation has been used to prime generative learning in computer-based learning environments. For example, in a computer game study, Pilegard and Mayer (2016) observed that participants in an experimental group that engaged in self-explanation activities outperformed a (non-self-explanation) control group on a transfer test (*d* = 0.74). Fiorella and Mayer (2015) reported that self-explaining showed an average effect of *d* = 0.61 across 54 studies.

Summarizing: while self-explaining is an in-the-process learning strategy, learners can be prompted to summarize the VR-based learning activity or exercise they experienced. By summarizing, students can organize their thoughts around the main ideas in the learning activity that they had just experienced. A study by Parong and Mayer (2018) suggested that summarizing activities after an immersive VR learning activity was beneficial to learning. They found that learners who summarized segments of a VR lesson outperformed those who did not.

Elaboration: a study by Vogt et al. (2021) showed that participants who were prompted to elaborate on the main ideas in a VR-based activity outperformed the control group in factual knowledge. Their findings indicate that elaboration, a generative learning activity, aided in the retention of information in a VR environment. Invariably, the introduction of generative learning activity into VR-based learning could prompt students to engage in germane cognitive processing and facilitate positive learning outcomes. Hence, the research and development of effective VRLEs of engineering contents must encompass studies that identify and investigate effective instructional and pedagogical approaches for fostering meaningful learning engagement in VRLEs.

Embodied Cognition and VRLE Research

Some educational theorists have proposed that learning processes are inextricably linked to our interactions with our learning environment. Embodied cognition refers to the phenomenon in which our bodies play a critical role in the learning process (Wilson, 2002). When students engage in embodied activities, such as gesticulating or moving their bodies, they activate mental representations that enable them to think about abstract concepts (De Koning & Tabbers, 2011).

Thus, embodiment is essential for learning in three ways: it reinforces conceptual representations, activates abstract concepts in long-term memory, and stimulates spontaneous mental simulations. However, for embodiment to be most effective, users must actively engage with the instructional content rather than passively observe it (Kontra et al., 2015). That is, learners must be primed to manipulate instructional content through gestures, drawing, and perspectives (FIORELLA, 2022).

Johnson-Glenberg (2018) advanced a set of design principles for embodied learning in VRLEs. The author proposed that VRLEs should be designed with the assumption that each learner is a “newbie”. In other words, designers of VR applications may introduce varying degrees of difficulty (Karaosmanoglu et al., 2021). It may be necessary to consider the learner’s level of expertise; for example, students with limited prior knowledge of instructional content may not be asked to participate in activities requiring a lot of movements until they have achieved some proficiency in the basic content. Glenberg also recommended that scaffolds be provided in a highly embodied environment, that guided exploration be incorporated, and that an opportunity for reflection be provided (Johnson-Glenberg, 2018).

Educational VR can enable foster embodied learning through physical movement within a VRLE. However, the embodied learning process is not well understood because embodied cognition research in educational VR is still in its infancy. For instance, little is known of the effects of object manipulation on the working memory (Paas & Sweller, 2012). As such, educators could benefit from studies that explores (to understand) embodied learning and cognition – and its effect on diverse types of learners. Research that helps us understand how to facilitate effective embodied pedagogies and learning in VRLEs is also needed. In the future, researchers may examine how to incorporate feedback and reflective activities into highly embodied VR environment, particularly – especially for promoting knowledge construction and promote positive learning outcomes in learners with limited prior knowledge.

Collaborative Learning in VRLEs

Collaborative learning occurs when two or more individuals participate in the process of learning. According to the social-cognitive framework, collaborative learning can foster a sense of self-efficacy and improve the collective problem-solving process of collaborating students (Francescato et al., 2006; Kim & Baylor, 2006). Several empirical studies have demonstrated the benefits of collaborative engagements on cognitive and affective learning outcomes (Laal & Ghodsi, 2012). Because the engineering profession is socially and collaboratively practiced, students get several team-based and collaborative learning opportunities and experiences during their engineering education career.

Educational VR technologies have several capabilities to support computer-mediated collaborative learning activities. (de Back et al., 2020). For example, students could collaboratively resolve engineering problems as they share resources and engage in immersive and embodied learning concurrently in collaborative VRLE activities. Studies that compare the gains of collaborative and individual learning in VRLEs have shown inconsistent results (Paas & Sweller, 2012). Hence, it is necessary for VR-related research to investigate relative individual learning, how collaborative learning occurs in VRLE. Future research may explore individual differences when learning from VR. For instance, de Back et al. (2020) found that spatial ability moderates the effects of collaborative learning in VR.

3.6 Potential Paths for Future VRLE Research in Engineering Education

The application of VR in entertainment and educational industries has increased astronomically in the last decade due to major advancements in computing capabilities and internet connectivity. VR is already being employed to facilitate pedagogy and learning in many educational contexts. This reality behooves engineering education stakeholders to start considering how to integrate VR-based learning and instruction at all levels of engineering education. Similarly, research on the use of educational technologies in engineering education must draw on relevant cognitive and non-cognitive learning theories to identify: (i) design principles for developing efficacious VRLEs of engineering contents; (ii) to identify activities that support meaningful students' engagements; (iii) promote positive cognitive and non-cognitive educational outcomes; and (iv) how to assess and evaluate learning objectives and outcomes in VLREs. Luo et al. (2021) argued that the effectiveness of VR-based pedagogy is contingent upon the design philosophies and principles upon with it is designed, developed, and implemented. Considering the foregoing, we propose the following as research imperatives, or potential directions for future instructional VR research in engineering education:

Exploring the mechanisms of learning in engineering VRLEs through the lenses of learning theories

As noted in section 3.3.3, we observed that many VR studies in engineering education sparsely (or rarely) draw on theory to investigate the design of VRLEs for engineering contents. Similarly, there scarcely are theory-informed studies that examine how students interact with learning material or tasks, and with other students in engineering-focused VRLEs. Magana (2022) emphasizes the importance of the theoretical and pedagogical framework in engineering education research. The author asserts that theoretical and pedagogical frameworks are critical components of instructional design and delivery, and that they lay the foundation for productive educational research and provide explanatory for understanding a phenomenon.

Echoing Magana (2022), Matusovich and Benson (2022) argued that explicit recourse to theory is critical to advancing the creation and communication of trustworthy knowledge in engineering education. Therefore, to gain better understanding of how to employ VR for effective engineering instruction and learning, we propose that the of future VR research must shift from merely admiring VR technology features and student perceptions of VR learning experience and dig deep in to understand the mechanisms that underly students cognitive and socio-cognitive engagement in VR environments. Drawing on learning, motivational, and pedagogical theories, future research may also explore how effective VR-based instruction for engineering education can be supported.

Exploring instructional methods in VR engineering education research

There is growing empirical evidence that multimedia and generative learning principles are effective in implementation and supporting VR-based instruction in the learning sciences and educational research literature. However, the technology-in-engineering educational research literature is notably trailing this research drive. Studies that examine the validity and robustness of these principles in facilitating engineering pedagogies are also essential to engineering education research and practitioner communities.

Because meaningful learning depends on effective instructional methodologies, and not on the media of instruction in and of itself (Clark & Mayer, 2016; Clark, 1994), we advocate for research that explores curricular and instructional imperatives for VRLEs for engineering educational. Several studies have examined the relevance of multi-learning theories and principles, and some studies have examined them in instructional VR application. In addition to exploring their relevance, future research should explore the boundaries conditions of VR-based pedagogy to clarify the strengths and limits of their educational benefits. For example, it is important to investigate the conditions (when, what, and for whom) under which VR-based instructions are effective, or ineffective.

Assessment of Learning Outcomes in VR Research

Our observation of the state of VR research in engineering education (Section 3) revealed that a disproportionate number of studies focus on usability and student perceptions of VR-based instructions. A few studies explored the effectiveness of VR-based instructions on cognitive, social-cognitive, and metacognitive learning outcomes. Considering this, studies that investigate the impact of VR-based instruction on different knowledge facets (conceptual and procedural understanding, application, and transfer of knowledge), retention (immediate and delayed recall), and psychomotor skills are needed. Additionally, research is needed in the future to whether VR-based instructions are better for lower-order or higher order thinking activities (Chen, 2016; Papanastasiou et al., 2019) as they learn from VR instructions.

Theorists have argued that media-related instruction should be learner-centered rather than technology-centered, that is, based on the study of how people learn from technology or how to promote learning (Clark & Mayer, 2016; Mayer, 2017; Mayer, 2020). We propose that future VR research in engineering education that examine students' engagement with learning task, content, and technology by triangulating cognitive, affective, and meta-data of students' moment-by-moment movements or interactions in VR space may be informative. Lastly, future studies may draw on the community of inquiry framework to explore how students interact with their peers and instructors during VR-based activities.

We hope that this article inspires a discussion about the value of a theoretical framework in research on VR engineering education and how instructional design principles can be used to predict and explain the unique affordances of VR instruction. We are optimistic that the fusion of VR-related instructional design, learning sciences, and engineering education will result in a fruitful and exciting area of research capable of advancing both theory and practice.

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CHAPTER 4

STUDY III: BENEFITS OF INCOPORATING A GENERATIVE ACTIVITY PRINCIPLE TO FACILIATE ENGINEERING SUDENTS' LEARNING EXPERIENCE IN A DESKTOP VIRTUAL REALITY ENVIRONMENT[3]

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[3] Oje A.V., Hunsu N., Dominik M., Savaddatti S. Submitted to Journal of Computer Assisted Learning, November 10, 2022

4.1 Abstract

There has been an increasing interest in the educational applications of Virtual Reality (VR) technologies, particularly in engineering education. Nonetheless, very little is known about how best to design and use VRs to facilitate learning in the most effective ways. Notably, there is a dearth of VR research studies that are grounded in empirically tested theoretical frameworks of multi-media learning within the engineering research literature. This study examines the learning effects of VR media on cognitive learning outcomes and the use of instructional design and generative activities to promote students' learning experience in an engineering statics desktop VR context. Thirty-eight college students were randomly assigned into intervention and control groups to learn engineering statics in three learning phases. The intervention consistent of students who learned with VR and conducted a generative activity. Results showed that students who used VR did not do better compared than those in a control group on declarative knowledge tasks when the VR activity was not scaffolded. However, results showed that students who learned in VR performed better than those in a control group on procedural knowledge tasks. Further, the study found that integrating a self-explanation task into VR learning activity significantly enhanced students' performance on a problem-solving task and fostered triggered situational and self-efficacy beliefs. The study also found that integrating a self-explanation– generative activity – in VR tasks reduced extrinsic and intrinsic cognitive processing. The study provides important implication for how educators and instructional designers implement evidence-based principles of generative learning to enhance problem-solving and facilitate the VR learning experience.

4.1 INTRODUCTION

4.1.1 Objectives and Rationale

Laboratory experience is essential to the professional formation of engineering students, thus has always been a crucial component of the engineering curriculum. This is the case because participation in laboratory activities are avenues for students to experiment and experience engineering theories and principles in practice (Seifan et al., 2020). Engineering laboratories facilitate conceptual understanding of numerous abstract engineering concepts. (De Jong et al., 2013). Similarly, student learn and hone procedure knowledge and skills they need to be employable and succeed in engineering careers. However, there has been questions recently about the instructional utility and value of alternative laboratory experiences that is less dependent on physical spaces and equipment for compensating (or even replacing in some cases) the traditional physical laboratory. The relevance of this radical views was further accentuated by the recent instructional disruptions that the COVID-19 pandemic caused. The COVID-19 disruption forced many instructors to consider alternative means for continuing to offer the educational experiences they have always provided despite the stringent lockdowns.

At the onset of COVID-19, some instructions at our institution explored the viability of virtual laboratory experiences that are facilitated through desktop Virtual Reality (VR). VR is a computer-facilitated realities that replicates the appearance and feel of the real world. It enables users to interact with virtual objects in a manner that mimics the experience that they could get in the real world. Many educational technology enthusiasts and researchers have proposed that VR can be advantageous to support experiential education in K-16 contexts (Suh & Prophet, 2018). As the technologies that support educational VR advance, there has been a growing interest and adoption of VR for learning in many STEM contents (Di Natale et al., 2020; Suh & Prophet, 2018). Furthermore, a number of VR environments that support virtual experimentation and laboratory activities as alternative laboratory experiences are less expensive to maintain. Although VRs is growing in popularity, and some early adopters of educational technologies are already using them in various ways for classroom instructions, there are currently very limited knowledge about how best to design and use them to facilitate learning in the most effective ways. Many prior VR studies have focused exploring the learning effects of VR relative to other media: using various VR media, such as desktop VR versus text (Makransky et al., 2019), immersive VR versus instructional video (Meyer et al., 2019), immersive VR versus desktop VR (Makransky et al., 2019), and immersive VR versus PowerPoint (Leder et al., 2019). However, the findings of these studies have been contradictory.

Some have suggested that VR could facilitate affective and emotional factors that enhance the learning experience (Parong & Mayer, 2021) in ways that other types of educational media may not. Because the learner can interact with the learning in a way that feels ‘real’, the learner can experience a perception of “presence” that enhance enjoyment of the learning task (Jang & Park, 2019). However, like any poorly designed educational technology, poorly designed educational VR may hinder, instead of enhancing the learning experience. For instance, some features of VR environments can distract learners from the most important instructional details (Parong & Mayer, 2018). Some learners may even find high immersion VR to be disorienting (Sharples et al., 2008). As such, not only are studies that explore how comparable VR media are to other instructional media, but there is also a need for studies that explores which evidence-based design and pedagogy principles may be leveraged for designing virtual learning environments (VRLEs) that are efficacious for learning. Apart from VR comparative studies, more studies that investigate VR learning experiences and the cognitive and affective factors that influence VR learning are needed.

Several studies have examined the benefits of VR in science education (Liu et al., 2020; Pirker et al., 2020). However, many of these studies have focused on media comparisons and students' perceptions of the VR experience to the exclusion of the interaction effects of VR media and the use of strategies that foster meaningful learning engagement. Consequently, some theorists have called for VR research that explore the effects of evidence-based design and pedagogical principles of cognitive processing and affective engagement on learning in VR media (Klingenberg et al., 2020; Makransky, 2021). Additionally, most prior VR studies have been conducted in the biological and learning sciences domains. Although VR technologies portend many benefits for formal and informal learning in engineering context, there have been very minimal effort to investigate the effects of design and pedagogical factors on VR learning in engineering studies. We argue that such studies could be informative for facilitating the design of VRLEs that pedagogy and learning of engineering contents. Although some champion that VRs may be effective for classroom and laboratory instructions, empirical evidence to support such claims are scant. As such, remains a significant gap in the literature regarding the capabilities of VR to promote positive laboratory experiences in engineering and related fields. Particularly, no study has compared the learning effects of VR to those of traditional engineering-based instruction.

The current study represents a first step in bridging this gap. In this study we hope to extend existing studies by examining how VR influences cognitive and non-cognitive outcomes that are essential in enhancing students' learning experience in engineering. This study aims to investigate whether the application of instructional design and pedagogy promotes students learning experience in an engineering Virtual Reality (VR) context. The study compares the learning effects of a desktop VR laboratory and traditional instructional approach on some important cognitive and non-cognitive outcomes when learners also engage in a generative learning strategy.

4.1.2 Literature Review

Cognitive learning theories

The Cognitive Load Theory (CLT) and the Cognitive Theory of Multimedia Learning (CTML) are two cognitive theories that describe how design features affect learner's cognitive processes and learning outcomes in multi-media learning environments (Mayer, 2020; Sweller, 2020). Both cognitive theories propose that learners have a limited cognitive processing capacity, and that learners' working memory is overloaded when the cognitive load induced my multi-media environments are not adequately managed (Mayer, 2017; Sweller et al., 2019). The CLT and the CTML proposes that multi-media learners may encounter three kinds of cognitive load in: intrinsic or essential load, germane or generative load, and extraneous load (Mayer, 2020; Sweller, 2005).

Because the human working memory has a limited processing capacity (Paas & Sweller, 2012), theorists propose that the multimedia learning contents and environments must be designed to reduce or eliminate unwarranted cognitive load, and thus minimize cognitive overload. However, because learning also depends on how students engage with learning, multimedia learning theorists further argue that multimedia contents and environments have a better impact on learning when they also incorporate instructional pedagogies and generative activities that promote elicit germane [cognitive] processing. Extant multimedia learning literature proposes that such pedagogies and activities are essential to foster sensemaking and understanding the multimedia instruction (Fiorella & Mayer, 2016). For example, some studies have demonstrated that including scaffolding prompts (such as guidance scaffolds) or requiring students to engage in self-explanation activities during multimedia learning can assist them to remain motivated and engaged in the learning process (de Jong, 2021; Fiorella & Mayer, 2021). Also including activities that foster germane processing have been shown to promote deeper understanding of instructional material in multimedia environment.

Self-explanation as an activity of generative learning

The generative learning theories (GLT) proposes that students learn more effectively when they engage in generative learning activities (e.g., summarizing, drawing, learning by teaching or self-explanation) (Fiorella & Mayer, 2015, 2016). The GLT emphasizes that learning occurs when learners select the most important details of an instructional material. Next, they organize those details by engaging in activities that engenders germane processing which enables them to integrate the processed information into their prior knowledge. Fiorella and Mayer (2016) argue that effective instruction must opportunities for students to engage in generative activities that induces them to select, organize and integrate the most important details of their instructional material

Self-explanations have been identified in the GLT literature as examples of generative activities that can engender germane processes that facilitates knowledge construction and enhance problem-solving. Learners activate prior knowledge and reflection deeply when they self-explain concepts to themselves (Atkinson et al., 2003; Johnson & Mayer, 2010). Some theorists argue that self-explanation enables students to elaborate on the meaning of specific learning contents (Renkl & Eitel, 2019) and better integrate the meaning that evolve from this activity with what they already know (Bisra et al., 2018). Prior studies have documented the direct and indirect effects of self-explanation on learning. For example, Kwon et al. (2011) found positive associations between self-explanation and student achievement scores. In a recent meta-analysis of 69 studies, Bisra et al. (2018) found that self-explanation a positive medium effect (*g* = .50) on learning. Fiorella and Mayer (2015) found that self-explanation had a positive effect on learning outcomes (Cohen *d* = 0.40) across a synthesis of 44 studies. Additionally, some studies have shown that the quality of the self-explanations that students make also moderate the effect of self-explanation (Berthold et al., 2009; Bethany et al., 2017).

Affective factors and multimedia learning

Learning is influenced by both cognitive and affective factors. In this section we describe theoretical perspectives of learning motivation that can directly and indirectly affect learning in VR. For example, students' motivation to learn may be influenced by their interest in learning. Interest significantly predicts how students engage (or reengage) with a learning material and activities, or whether they will persist on task relevant activities (Dweck, 1986; Dweck & Leggett, 1988). In the following subsections, we explain the relevance of self-efficacy and situational interest to the current study.

Self-efficacy: Bandura's self-efficacy theory asserts that students exert effort in instructional activities when they are confident in their ability to complete and succeed at a task (Bandura, 1982; Bandura & Cervone, 1986). Students with high self-efficacy are confident in their ability to perform success-related tasks, whereas those with low self-efficacy may be less inclined to engage in success-related activities (Linnenbrink & Pintrich, 2003). As a consequence, students with low self-efficacy may adopt maladaptive behaviors that further undermine their ability to succeed. Prior studies have shown that self-efficacy engenders self-regulatory behaviors (Zimmerman et al., 2017), ensuring that learners with high self-efficacy put in the effort they need to succeed at learning-related activities and tasks (Komarraju & Nadler, 2013).

Besides the fact that educational VR can provide unique perspectives about abstract concepts that make them 'real' and accessible to grasp, they can also offer low risks learning environments where it is safe for students to fail in engineering laboratory instructions. As such, learners may be more confident in their ability to complete learning and laboratories activities in VR. Researchers have examined the effect of VR media on students' self-efficacy to learn (Huang, 2022; Lin & Wang, 2021; Thisgaard & Makransky, 2017). Students with a high self-efficacy may feel more confident completing learning tasks in VR media than students who are less familiar with VR media and who may have a low self-efficacy about learning in an unfamiliar environment. For example, Meyer et al. 2019 found that students who were provided pre-training opportunities before participating in a VR activity reported higher self-efficacy for learning than those did not. Lastly, some prior studies have examined indicated that engaging in generative learning activities can foster self-efficacy for learning (Brüssow & Wilkinson, 2007; Klingenberg et al., 2020; Mirriahi et al., 2021). In this study, we will extend previous research by investigating how engaging in self-explanation tasks affects students' self-efficacy in a desktop VR environment.

Situational Interest: Situational interest describes the psychological state of being engaged and the propensity to reengage with a particular topic or activities that are caused by interesting features of the learning environment that pique learners' curiosity to learn (Ainley, 2019; Hidi & Renninger, 2006). Situational interest is said to be triggered when some interesting detail of the learning content or environment stimulates learning enjoyment and causes the learner to fully engage or return to engaging with learning. Theorists argue that situational interest can influence students' affective engagement and stimulate achievement behaviors (Schraw et al., 2001). Hence, engendering situational interest could enable students to be actively involved with the learning activity (Palmer et al., 2017).

Hidi and Renninger (2006) posits that that situational interest evolves through two states – triggered and maintained situational interest states. Situational interest is stimulated when learner's interest is elicited or by stimuli they receive from details of an instructional material or the design or presentation of a learning environment (Hidi & Renninger, 2006). On the other hand, maintained situational interest describes the heightened state of interest that learners experience because the learning activity or material has captured their attention, even after the trigger has been removed. Maintaining situational interest is a function of the content or nature of the learning activity, instead of its design and presentation (Linnenbrink-Garcia et al., 2010). Learners are the more likely to internalize and personalize their affection for an activity or a subject when situational interest is maintained over time.

According to theorists, interesting learning environments are one of the hypothesized triggers or sources of situational interest. Drawing on this perspective, some have argued that the emotional appeals of VR environment can trigger learners' situational interest in ways that traditional instruction cannot (Makransky et al., 2020). In addition to the VR appeal, we argue that coupling generative learning activities with VR learning may engender situational interest in students. Although VRLEs have the potential to stimulate situational interest, and thus learning engagement, very few studies have tested this proposition empirically. Furthermore, we know little about how including a generative learning activity in VR learning will affect situational interest. This study examines the extent to which integrating a generative activity into learning with a desktop VR can facilitate situational interest in an engineering context.

Related Research

A few prior studies have examined whether desktop VR and simulations have comparable effects on learning as traditional instruction media (Merchant et al., 2014; Wu et al., 2020). Some studies have reported that immersive VR experiences improve student learning (Buttussi & Chittaro, 2017; Chen et al., 2019). Conversely, others have found that students who used immersive VR reported lower learning outcomes compared to those with traditional instruction (Chittaro & Buttussi, 2015; Makransky et al., 2019; Parong & Mayer, 2018). Because the findings of those studies having been contradictory, no definitive answers can be deduced about how effective VRs are for learning and the factors that moderate their learning effects from the existing body of empirical studies.

Using educational technologies alone to support education does not necessarily translate to learning. Equally important for learning is how educational technologies are designed and integrated with relevant pedagogies to support learning engagement (Clark et al., 2016; Clark & Mayer, 2016; Makransky, 2021). Unfortunately, very few studies focused on examining how evidence-based multimedia design and instructional principles impact learning in VR (e.g., (Klingenberg et al., 2020; Meyer et al., 2019; Parong & Mayer, 2018)). For example, Zhao et al. (2020) examined the benefits of supporting VR learning with a relevant generative learning activity on learning in a biology course. They observed that students who were asked to summarize after participating in the VR activity reported experiencing lower cognitive load. Parong et al. (2018) reported that students who were asked to summarize during a VR activity break performed better on factual and conceptual understanding tasks than those that did not. Makransky et al. (2020) examined the learning effect of engaging task-related enactment activities during a VR training. They found that learners who participating in the enactment activity performed better on procedural knowledge and transfer tasks than those that did not.

They concluded that the generative activities (e.g., enacting) during VR learning can improve cognitive outcomes. However, enactment effect on task enjoyment, presence or declarative knowledge was insignificant. Klingenberg et al. (2020) observed that students who participated in a learning by teaching activity in a biology VR task performed better on knowledge retention and transfer than those that did not.

The studies highlighted above reported that engaging VR learners in generative activities have positive effect on some cognitive and affective outcomes. However, most of these studies are conducted under controlled laboratory conditions. Furthermore, the studies are primarily within a specific domain and under a limited situation – none focused on the learning of engineering material. As such, we still do not know much about the effects, and how effectively generative learning activities enhance VR learning. Given these limitations and literature gap, there is need for studies to examine the learning effects of VR under laboratory and classroom conditions, especially in engineering contexts. There is also a need for studies highlighting the benefits of integrating generative activities into VR learning to maximize learning efficacy.

Current Study and Predictions

The present study seeks to address gaps in the VR literature about the learning effects of VR media and the use of generative learning activities when learning in VR media. Self-explanation was adopted because it was the most relevant and convenient generative learning activity for content area we examined. The VR learning platform was a desktop VR environment of a statics engineering concept. We explored how learning the engineering content with the desktop VR compared to the status quo. We also examined whether including self-explanation tasks influenced students' cognitive processing, problem-solving and affective outcomes. Extraneous, intrinsic, and germane loads were assessed as measures of the cognitive processing outcomes. Our study endeavored to address the following research questions:

RQ1: To what extent does VR facilitate declarative and procedural knowledge in an engineering statics lesson compared to a traditional instructional medium?

RQ2: Does adding a self-explanation as a generative learning activity to the VR learning activity improve students' problem-solving skills relative to traditional instructional medium?

RQ3: Does the addition of a self-explanation–generative learning activity enhance affective outcomes (by stimulating and sustaining situational interest and by fostering self-efficacy)?

RQ4: Does the addition of self-explanation- generative learning activity influence cognitive processes (intrinsic, extraneous, and germane cognitive load)?

Table 4.1 shows our hypotheses based on theoretical assumptions drawn from extant multimedia literature. The deep learning hypothesis suggests that students who learn in VR are more likely to be motivated to exert effort during instructional activities, and such exaction of effort would enhance their learning (Makransky et al., 2019; Moreno & Mayer, 2002). Drawing on the deep hypothesis and findings of previous research, we anticipate that the VR group will perform better on procedural knowledge (Hypothesis 1c), but not in declarative knowledge (Hypothesis 1a). However, we anticipate that providing scaffolds prior to a VR activity would aid declarative knowledge (Hypothesis 1b).

Next, based on the generative activity hypothesis, we anticipate that including a generative activity as part of VR learning activities would enhance students' problem-solving skill (Hypothesis 2). Additionally, based on the motivation hypothesis grounded in the interest and self-efficacy literatures, we expect that self-explanation will facilitate situational interest (Hypothesis 3a), and self-efficacy (Hypothesis 3b) outcomes.

Lastly, drawing on the cognitive processing hypothesis, we expect that self-explanation would reduce extraneous processing (Hypothesis 4a), increase germane processing (Hypothesis 4b), and be effective for managing or offloading intrinsic processing (Hypothesis 4c).

4.2 METHODS

4.2.1 Participants and Design

Participants for this study were 38 second-year undergraduate students who enrolled in two sections of statics in the college of engineering at a public university of a southeastern state of the U.S. Participants' mean age was 20 years (*SD* = 2.19). About 16% of the participants were females. The study was approved by the university's institutional review board and followed its ethical guidelines.

Sensitivity analysis was conducted using the effect size of generative activity (Cohen's *d* = 1.12) reported by Parong and Mayer (2018) to determine the sufficiency of our sample size for our analysis. The analysis was conducted using the G*Power 3.1.9.6 application at an alpha level of 0.05, and power (1- β) = 0.95. The power analysis indicated that 36 participants were adequate to detect the expected effect. Following the analysis, 19 students were assigned to receive an intervention group that learned with VR and conducted self-explanation activity (generative strategy + media), and 19 students were put in the control group that did not receive a VR intervention and did not do a self-explanation activity. Participants did not differ (*p*-values > 0.05) on measures of spatial knowledge, prior virtual experience, and prior knowledge before the intervention.

4.2.2 Materials

Desktop VR Excavator: The VR simulation, Collaborative Analysis and Design for Engineering Statics Education (Figure 4.1) used in this study was developed by the Virtual Experiences lab at the university. The VR simulation was developed to facilitate the learning of the statics concepts in engineering. The desktop VR platform depicts an excavator that students could manipulate, measure lengths, and identify static forces needed to complete a free body diagram activity.

AB: 53.841 m
BC: N/A
B: N/A
P.x: N/A
P.y: N/A
P.z: N/A

Rotate Arm 0.50
Pitch Arm 0.45
Bend Arm 0.00
Bend Wrist 0.00
Pitch Shovel 0.50

Model: Excavator Current: Excavator
Config: Preset Current: Preset

Figure 4.1: Excavator in the desktop VR Environment

4.2.3 Measurements and Scoring

An assessment instrument was administered pre-intervention to obtain demographic information such as: age, gender, major, race/ethnicity, and transfer status. Measures of spatial ability, prior virtual experience, and background knowledge for working with complex and real-world engineering problems.

Prior experiences: Two measures of prior experience were administered. Participants' prior experiences working with engineering drawings and modeling, and prior knowledge with solving statics problems was assessed on a 7-point Likert scale using four items. (See Appendix A) Examples of these items included, "I have a lot of knowledge about modeling engineering problems," "I have a lot of experience working with detailed engineering drawings", "I have a high level of knowledge about statics problems". Prior exposure or experience with VR environments was assessed on a 7-point Likert scale. Examples of items on the subscale included

"I have a great deal of experience with VR environments in the context of solving engineering problems". The scores for the prior experience subscales were obtained as an aggregated sum of the item scores for each subscale. Because prior experiences and prior knowledge can affect learning outcomes, the prior knowledge and experiences scores were compared to determine whether the groups were similar prior to the intervention.

Spatial Ability: Participants' spatial ability was assessed using the Santa Barbara Solids Test (SBST). The SBST comprises ten questions about various configurations of shapes that require varying degrees of rotations and translations to solve. Participants were required to select which cross-sectional area depicts the shape of a 3-D object from four possible options (See Appendix B). The SBST scale is considered useful for assessing engineering students' spatial ability (Cohen & Bairaktarova, 2018; Yeaman et al., 2018).

4.2.4 Learning performance and post-activity measures

Learning performance tests: Participants' performance was assessed for how accurately they drew a free body diagram of the excavator, identify problem attributes (forces and lengths measures) to facilitate a subsequent problem-solving task related to accurately resolving forces at equilibrium. The free body diagram task was intended to assess declarative knowledge – participants were required to draw two-dimensional representations of the forces acting on the excavator as they observe its three-dimension model. They were to ignore irrelevant or insignificant forces and dimensions. The procedural knowledge test comprised nine questions that prompts students to identify and estimate relevant attributes (lengths and forces) that they would need to resolve the forces acting around points on the excavator. Finally, three questions assessed how well students could apply their knowledge of statics concepts, given the attributes they had identified, to solve a novel engineering statics problem. The content validity of the assessment was based on the expert opinion of two instructors that have taught statics and other mechanical engineering courses for more than 10 years. Participants' solutions were assessed using a 4-point scale rubric – with a maximum of 12 total points obtainable.

Post-activity measures: After the intervention, participants received a 17-item questionnaire that assessed situational interest, self-efficacy, and cognitive load. They were asked to rate a series of statements on a 7-point Likert scale that ranged from 1 (strongly disagree) to 7 (strongly agree). The situational interest scale (adopted from (Wang & Adesope, 2016)) consisted of 4 items that assessed triggered situational interest. Examples of items included "I think the excavator project was interesting." The internal reliability of the scale was good, Cronbach's $\alpha = .76$. The scale also included 5 items that assessed maintained situational interest. Examples of items included "The excavator project was so interesting that I would have continued working on it even if an interruption occurred." The internal reliability of the scale was good, Cronbach's $\alpha = .80$. The self-efficacy scale included items (adopted from (Huang, 2019)) consisted of 6 items that assessed student's confidence in their abilities to understand science and engineering concepts. Examples of items included "As a result of this excavator project, I am confident that I can understand the basic concepts of statics." The internal reliability of the scale was good, Cronbach's $\alpha =.93$. The questionnaire also included items (adopted from (Leppink et al., 2013)) that assessed cognitive processing. The sub-scales included: three items that assessed extraneous cognitive load (e.g., "The design of the excavator project was very inconvenient for learning" Cronbach's a = .76); two items that assessed intrinsic cognitive load items (e.g., "The design of the excavator project was very complex," Cronbach's $\alpha = .53$); and three germane load items (e.g., "The learning task in this excavator project consisted of elements supporting my comprehension of the task," Cronbach's $\alpha = .68$).

4.2.5 Procedure

Participants who enrolled in sessions of the statics course examined in this study did so to fulfil a graduation requirement of their programs. The study was conducted in the context of weekly class activities for the course and data collection was done at three time points. Participants were briefed about the structure of the learning activities at the start of the study. They were randomly assigned into intervention and control groups during the 13th week of the semester. All participants received a Qualtrics link to a pre-intervention assessment that measured their prior knowledge and prior experiences. Along with the pre-intervention survey was a consent form that explained the purpose of the study and informed participants about their rights to continue or withdraw from the study and about how their data will be handled.

The study was completed in three phases. The first phase involved an exploration exercise. Participants in the VR condition were prompted to explore the desktop VR tool to observe the different parts and navigation controls of the virtual excavator. Those in the control group watched a video that described different parts of an excavator and how it operates. Both groups received questions that prompted them to create an idealized model of the excavator after exploring it.

The second phase was an intervention phase where participants in the VR condition interacted with the virtual excavator to collect the data they needed for their analysis. Unlike in the exploratory phase, they were scaffolded on navigating the platform by on-screen text instructions that provided information on how to navigate the VR tool and measure dimensions that were necessary for solving subsequent problem-solving. Participants in the control condition received a detailed engineering drawing with measurements of an excavator. The measurements were adapted from a factsheet from Caterpillar® (See Figure 4.3). Students in the control group had unrestricted time to complete their tasks without any Instructor supervision. Both groups were required to independently identify and estimate the necessary attributes they would need to solve a subsequent novel problem.

In the final phase of the study, students who received the VR intervention also received a self-explanation prompt that required them to self-debrief their experience. The self-explanation exercise required them to reflect on their interactions with the virtual excavator and explain to themselves the steps they took in obtaining the attributes that they deemed as relevant to their subsequent problem-solving tasks. Next, both conditions received questions that required them to apply static engineering knowledge and principles that they have previously learned to solve a novel engineering problem. Lastly, all the students completed a post-intervention survey that measured situational interest and cognitive processing. The entire study lasted 1.5 weeks.

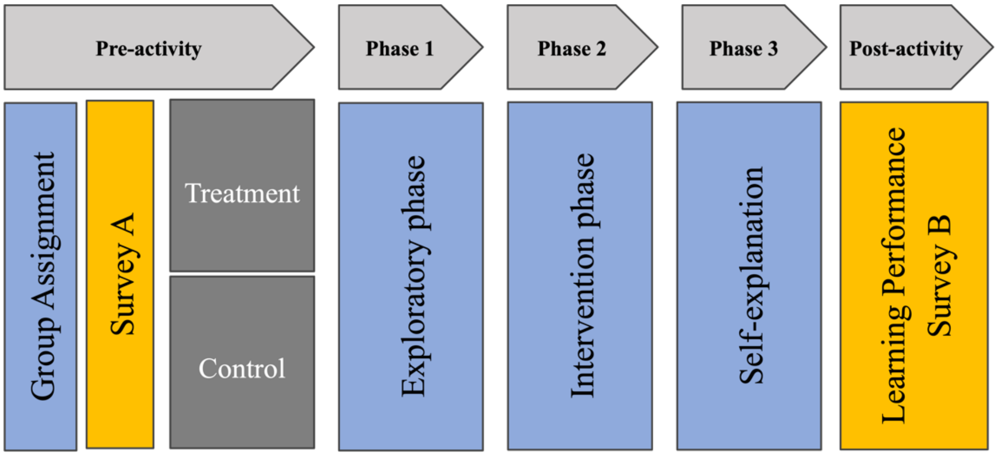
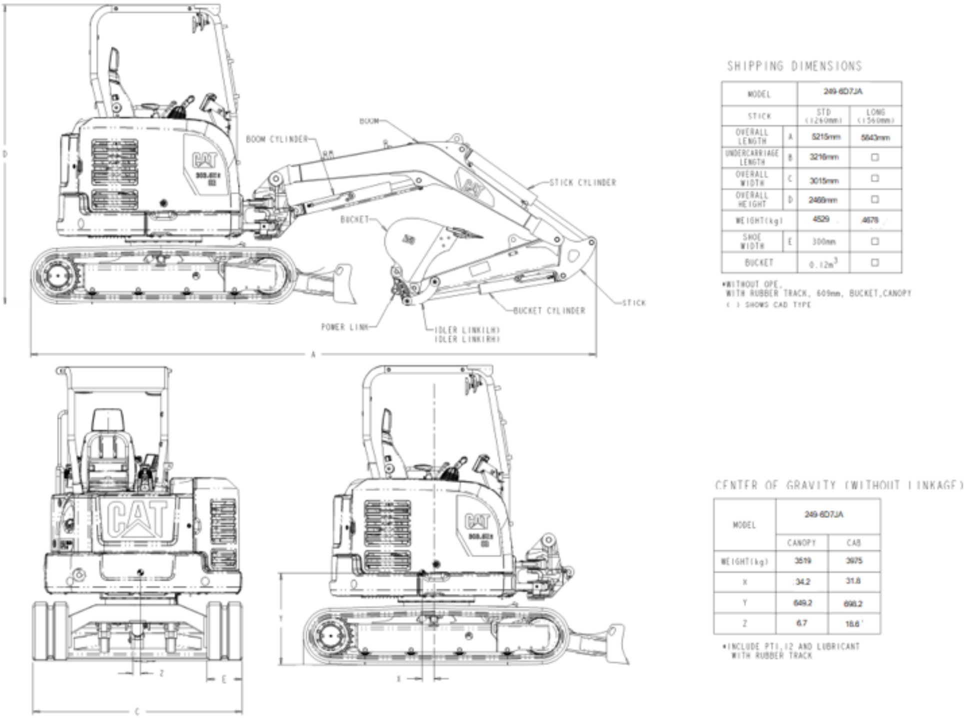


Figure 4.2: Study phases and experimental procedure

4.2.6 VR Simulation self-explanation activity

The self-explanation prompt was created in collaboration with two research faculty, a graduate student, and a content-knowledge expert who is a statics instructor. The participants were prompted to type their self-explanations after reflecting on the course material, procedures, and the learning activity they had engaged in. Specifically, the participants were to list and explain the steps they took in creating the simplified model and estimating all necessary dimensions. They were also required to identify relevant statics principles that they would use to solve a novel static problem that had been assigned, and to explain why they thought those principles were relevant. The self-explanation data was collected in open-ended response format via a Qualtrics platform.



SHIPPING DIMENSIONS

MODEL		249-6D7JA	
STICK		STD (1260mm)	LONG (1560mm)
OVERALL LENGTH	A	5215mm	5843mm
UNDERCARRIAGE LENGTH	B	3216mm	☐
OVERALL WIDTH	C	3015mm	☐
OVERALL HEIGHT	D	2468mm	☐
WEIGHT(kg)		4529	4678
SHOE WIDTH	E	300mm	☐
BUCKET		0.12m^3	☐

*WITHOUT OPE.
WITH RUBBER TRACK, 609mm, BUCKET,CANOPY
( ) SHOWS CAD TYPE

CENTER OF GRAVITY (WITHOUT LINKAGE)

MODEL	249-6D7JA	
	CANOPY	CAB
WEIGHT(kg)	3519	3975
X	34.2	31.8
Y	649.2	698.2
Z	6.7	18.6

*INCLUDE PTI,12 AND LUBRICANT
WITH RUBBER TRACK

Figure 4.3: Engineering drawings of excavator with measurements

4.2.7 Data Analysis

One-way analysis of variance (ANOVAs) was conducted using the IBM SPSS® Version 28 to compare the groups on the variables examined in the study. Prior to the analysis, normality assumptions were tested – most of the learning outcome variables satisfied the normality and the homogeneity of variance assumptions. As such, we proceeded with using ANOVA to compare the groups on those variables because of its robustness to the violations of normality when sample sizes are equal (Blanca Mena et al., 2017; Schmider et al., 2010). The affective and cognitive processing measures did not satisfy the homogeneity of variance assumption. To make the model for the analysis of these variables robust to data violations (such as outliers and violations of normality assumptions), we used a robust Bayesian estimation model, with a prior t-distribution. Bayesian methods employ likelihood distribution intervals rather than point estimators (*p*-values). Doing so reduces the dependence of statistical inference on statistical significance, as some have argued that p-values have little clinical relevance (Cleophas & Zwinderman, 2018).

Because of ongoing debates about the relevance of significance levels and the p-value (Bowman, 2017; Sullivan & Feinn, 2012; Tomczak & Tomczak, 2014), we refrained from using the "statistical significance" and "non-statistical significance" terms. Rather, we chose to report effect sizes (Cohen's *d*) of group comparisons in addition to reporting the conventional *F* tests of comparison. Cohen's *d* was classified into three categories: small ($d = 0.2$), medium ($d = 0.5$), and large ($d = 0.8$). Effect sizes greater than 0.4 may have educational significance (Hattie, 2008; Mayer, 2016).

4.3 RESULTS

4.3.1 Preliminary analysis

Prior to exploring the research questions, we examined whether there were pre-existing differences between groups despite random assignment. Independent sample t-tests indicated there were no significant differences in the prior knowledge, prior experience, or spatial ability scores of the groups. Since the groups were not different on these variables, we did not used them as statistical control variables in the main analysis.

4.3.2 Hypothesis 1a and 1b: To what extent does VR facilitate declarative knowledge?

First, we predicted (H1a) that students in the VR group will not outperform students in the control group on declarative knowledge during the unguided exploration phase. Table 4.2 shows the mean and standard deviation of the group scores for declarative knowledge. A one-way between-subject ANOVA revealed there was no statistical difference between the VR and control conditions on measures of declarative knowledge F (1,37) =.54, p >.05, η^2=.01). Overall, there was no significant difference between the mean learning performance scores of students in the VR group (M = 6.58, SD = 3.22) and students in the control group (M = 5.89, SD = 2.47), effect size of d = 0.24.

Second, we predicted that students in the VR group will outperform those in the control group on declarative knowledge (H1b) when they receive scaffold prompts that guided their activity. A one-way between-subject ANOVA revealed a borderline statistical difference between the VR and control groups after guided scaffolding was provided, F (1,37 = 3.78, p = 0.06, η^2=.09). The mean performance score of students in the VR group (M = 8.68, SD = 2.67) was higher than the mean learning performance score of students in the control group (M = 7.05, SD = 2.51), and the effect size (d = 0.63) of the group difference was medium. Overall, the data partially supports the first hypothesis.

4.3.3 Hypothesis 1c: To what extent does VR facilitate procedural knowledge?

We included the knowledge score from the first phase as a covariate in the subsequent phase in order to control for the prior knowledge due to encountering the activity. As a result, an Analysis of Covariance (ANCOVA) was performed using procedural knowledge scores as the dependent variable. Estimated marginal means (EMMs) for the ANCOVAs are reported (See Table 4.2). ANCOVA results revealed a statistical difference between the VR and the control groups, F (1,35) = 14.16, p <. 001, η^2 =.29). Overall, the mean performance score of students in the VR group (*EMM* = 6.75, *SE* = 0.42) was higher than the mean performance score of students in the traditional group (*EMM* = 4.46, *SE* = 0.42) – effect size for the comparison was large (*d* = 1.29). The data supports our hypothesis showing a positive effect of VR on procedural knowledge.

4.3.4 Hypothesis 2: Does the addition of self-explanation as a generative activity improve problem-solving skills?

We predicted that adding a self-explanation task will improve students' problem-solving skill, based on the generative hypothesis (H2). Table 4.3 shows the mean and standard deviation of comparisons between group score for knowledge application. An ANOVA revealed a significant difference between groups, $F\ (1, 37) = 8.97$, $p < .05$, η^2=.20). Overall, students who engaged in self-explanation performed better on the problem-solving task assigned in the study (*M* = 8.47, *SD* = 2.59) than those in the control group (*M* = 6.26, *SD* = 1.90), effect size was large (*d* = 0.95). The data support the second hypothesis showing that generative activities facilitated the application of mathematical and engineering principles to solve novel engineering problems.

4.3.5 Hypothesis 3a and 3b: Does the addition of self-explanation as a generative activity enhance affective outcomes?

Based on the generative hypothesis, we predicted that adding self-explanation tasks would induce situational interest and increase participants' self-efficacy. The results of an analysis conducted using a robust Bayesian estimation model with an assumed unequal variance indicated that participating in self-explanation activities triggered situational interest in participants, relative to the control group ($\beta_{\text{Posterior}}$ =.62). However, the 95% confidence interval range for the difference was (-0.01 to 1.25), indicating that the difference may not be significant. Furthermore, self-explanation was associated with a higher maintained situational score as compared to the control group ($\beta_{\text{Posterior}} = 0.33$). The 95% confidence interval for the analysis ranged between -0.39 to 1.05, indicating that the effect was not significant. Bayes factor for triggered situational interest was 2.8. Jeffreys (1961) guidelines for interpreting Bayes factors proposes that factor index between 1 and 3 can be interpreted as supporting anecdotal evidence of an alternative hypothesis. Hence, despite the confidence interval range associated with the group comparison for triggered situational interest, we argue that our data provides some evidence that participating in self-explanation activities might have caused a higher triggered situational interest in the VR group relative to the control.

Relative to the control, the intervention and self-explanation group reported significantly higher self-efficacy scores than those in the control group, $\beta_{\text{Posterior}} = 0.73$, 95% CI [0.10, 1.35]. Consistent with the generative hypothesis, the data provides evidence to support the hypothesis that adding a generative activity into VR learning had a large effect on self-efficacy ($d = 0.78$). Overall, students who self-explained as they processed VR content experienced significantly higher self-efficacy and triggered situational interest. However, they were similar to the control group on maintained situational interest.

4.3.6 Hypothesis 4a, 4b and 4c: Does the addition of self-explanation influence cognitive processes (intrinsic, extraneous, and germane cognitive load)?

We hypothesized that asking students who learn in VR to do self-explanations would increase generative load and lower intrinsic and extraneous loads, relative to the control group. Consistent with these predictions, the self-explanation activity reduced extraneous cognitive load significantly, $\beta_{\text{Posterior}} = -1.1053$, 95% CI [-1.97; -0.24], $d = -0.86$. It also reduced perceived intrinsic cognitive load, $\beta_{\text{Posterior}} = -1.3684$, 95% CI [-1.97; -0.24], $d = -1.56$. Differences between the intervention and control groups on germane load was not significant (See Table 4.4). Invariably, integrating self-explanation activity in VR learning had desire effects on cognitive processes by reducing intrinsic and extraneous cognitive load. The results partially support the cognitive learning hypothesis.

4.4 DISCUSSION

The first objective of the current study was to compare the effects of learning with a desktop VR to the traditional approach to learning in engineering statics on declarative and procedural knowledge. The study builds on the findings of prior studies that investigated the learning efficacies of instructional VRs (Parong & Mayer, 2018; Parong & Mayer, 2021; Petersen et al., 2020; Thisgaard & Makransky, 2017). Additionally, it extends the body of evidence about VR learning to engineering learning contexts. We found that participants in the VR group did not do better than those in the control on declarative knowledge scores where the VR activity was not scaffolded during an exploratory phase. This observation replicates the findings reported in prior studies that showed that learning in VR did not improve students' declarative knowledge in various educational domains (Klingenberg et al., 2020; Parong & Mayer, 2018). However, a medium effect was observed when the VR participants were scaffolded to use the VR tool. The finding also supports prior research that showed a positive effect of guided scaffolds in educational VR applications (Chen & Ismail, 2008; Ullah et al., 2016).

Theorists have suggested that scaffolds and instructional supports make learning in simulated environments effective (Smetana & Bell, 2012). Our data revealed that students in the VR condition found the scaffolds beneficial because they were able to easily identify the attributes needed for problem-solving in the VR application. By implication, VR, in and of themselves, like any other educational technology tools, may not always be beneficial for learning, especially when used as a discovery or exploratory learning tool. Some theorists have argued that discovery-based (or minimally guided) learning is not instructionally effective (Kirschner et al., 2006; Sweller et al., 2007). These results highlight the significance of scaffolding the use of instructional VR to support learning. Furthermore, we observed that learning in VR had a positive effect on procedural knowledge. This finding is consistent with those reported by previous research that VR learning improved procedural knowledge (Abich et al., 2021; John et al., 2018; Klingenberg et al., 2020; Li et al., 2017).

The second objective was to examine the learning effect of including a generative activity in VR learning on participants' ability to apply their prior knowledge to solve a novel problem. This observation builds on previous studies that examined the learning effects of generative activities in VR environments (Klingenberg et al., 2020; Makransky et al., 2020; Zhao et al., 2020). Our study revealed that integrating a self-explanation task into a VR learning activity enhanced problem-solving abilities. Similar findings about the positive effects of generative activities on VR learning have also been reported in prior studies (Makransky et al., 2020; Parong & Mayer, 2018; Vogt et al., 2021). For example, Parong and Mayer (2018) found that students who were asked to summarize a biological lesson in VR performed better in knowledge acquisition than those that did not. Makransky et al. (2020) reported that students who engaged in enacting activities while learning in VR environments performed better on transfer tasks than those who did not.

Our observation about the self-explanation effect on VR learning extends the body of current evidence that integrating generative activities into VR learning has a positive learning effect. Our result also supports theoretical assertions and results of prior studies about the benefits of self-explanation to foster problem-solving skills in traditional multimedia environments (Fiorella & Mayer, 2016; Kwon et al., 2011). Based on these finding, we may infer that self-explanations can facilitate the successful implementation of VR-based instruction in engineering education.

No prior study had previously examined the effects of generative activities on situational interest in VR. Contrary to our predictions, we found that self-explanations did not significantly foster situational interest. It is worth noting that the data showed that students who self-explained after the VR activity scored higher on the situational interest scales than those that did not. Based on the confidence intervals however, the evidence was not sufficient to conclude that the differences between the conditions was statistically meaningful. Although the evidence is weak, there was anecdotal support in the data to suggest that adding generative activities to VR-based instruction might engender triggered situational interest. Our observation reflects the findings of prior studies that following up VR learning with generative activities had negligible effects on student attitudes and emotions (Fiorella et al., 2019; Makransky et al., 2020; Parong & Mayer, 2018; Zhao et al., 2020). For example, engaging in summarizing (Zhao et al., 2020), learning by teaching (Fiorella et al., 2019), enactment (Makransky et al., 2020) and practice testing (Parong & Mayer, 2021) had no significant effect on learners' interest, motivation and affective engagement in prior studies.

We also observed from our data that the use of self-explanation fostered self-efficacy belief. This observation is consistent with findings in some prior studies that instructional design can engender self-efficacy beliefs in traditional multimedia and VR media learning environments (Meyer et al., 2019). Our study makes a novel contribution to the field because it extends the research of VR learning to the engineering domain. From the findings of this study, we infer that adding self-explanation tasks to VR-based engineering instruction can improve students' confidence in their own abilities to comprehend and apply engineering principles to solve problems.

With respect to the third research question, we found that self-explanation reduced both intrinsic and extraneous cognitive load when learning in VR. This finding has significant theoretical implication for how we understand or manage cognitive load in educational VR environments. However, some of our findings contradicted some prior studies on the cognitive effects of generative activities. For example, while we observed that self-explanation reduced extraneous load, Parong and Mayer (2021) found that students who engaged in practice testing activities reported experiencing higher extraneous load than those that did not. However, it is unclear how features of the generative activity they introduced in their study affected the cognitive processing of participants in their study. It appears that stopping students unnaturally during the activity, as they did in their study introduced conditions that probably heightened cognitive load. Hence, it may be that different types of generative activities, how they are implemented, and the fidelity of that implementation may have practical consequences on cognitive processing, and thus cognitive load.

Furthermore, their study focused on contents in the biological domains. Hence, it is unclear how the main and interaction effects of learners' familiarity with specific generative activities and domain content affects extraneous processing. For instance, students learning some arcane engineering contents who are required to draw concept maps (a type of generative activities) to support their learning may find not only the engineering content complex to digest but may also struggle with concept mapping if they have had very minimal skill with drawing meaningful concept maps. Such hypothetical scenario may have implications for the extraneous and intrinsic loads associated with the learning situation. Given that the CLT does not address the effect of generative activities on extraneous processing, future studies that investigate how different generative activities affect extraneous cognitive processing may be needed.

Furthermore, we found that students who participated in the self-explanation task following the VR activity experienced lower intrinsic load compared to those in the control condition. Some theorists argue that asking students to self-explain their solution can reduce the amount of element interactivity, and thus reduce the intrinsic load, that learners experience while processing a learning material (Sweller, 2010). Contrary to our observation, Parong and Mayer (2018) reported that engaging in practice testing (as a generative activity) had no significant effect on intrinsic load for participants in their study. However, Zhao et al. (2020) found that participants who engaged in summarizing (as a generative activity) experienced lower intrinsic load. These observations further support our conclusion that different generative activities and the difficulty level of domain contents may have differential main and interaction effects on learners' cognitive processing and cognitive load.

Lastly, contrary to our predictions, our findings revealed that requiring self-explanation tasks had no significant effect on germane load. This observation is similar to that found by Parong and Mayer 2018 – they found that practice testing had no significant effect on generative processing. It is unclear why there was no significant difference between the groups in our study as we hypothesized. However, it appears that students who received traditional engineering instructions were also impelled to engage in generative efforts that enabled them to identify the most important details from the excavator datasheet that they were given. Alternatively, the virtual excavator model was more vivid and readily cognitively accessible to the imaginations of participants in the VR group. As such, self-explanation could not have provided any detail above and beyond what the VR environment afforded. Because germane load is related to the effort students expend in making sense of instructional materials, students who used the VR medium were unlikely to have expended more effort in constructing a mental image of the virtual excavator. Thus, they may have done less germane processing than those in the control group. Invariably, it is not unlikely that instructional content type may moderate the effect of generative activities on germane load. The likelihood of such effects may be explored in the future studies. Overall, our data partially supports the hypothesis that generative activities influence cognitive processing.

4.5 LIMITATIONS AND FUTURE RESEARCH DIRECTIONS

The unique observations made in this study could have significant theoretical and methodological implications for future studies. However, we recognize that our findings should only be considered within the contexts of the limitations of our study. First, this study was conducted in an engineering learning context, and it was based on a small sample size. These features limit the generalizability of our observations to other contexts. Future studies that draw on larger sample sizes, and in other domains can explore the robustness of our findings to broader learning situations. Due to our small sample size, we were only able to design a two-group (VR + self-explanations vs control) between-subjects study to investigate the learning effects of media and generative learning activities. As a consequence, we were unable to isolate the individual and interaction effects of VR and self-explanation on the learning variables examined in this study. Future research can examine the differential and interaction effects of media and instructional pedagogies on engineering students' VR learning outcomes using more elaborate research design (e.g., a 2 x 2 factorial design) that require a larger sample size.

The current study was conducted under classroom conditions that lack the same controls that laboratory settings afford. Secondly, our study was conducted in the context of learning in desktop VR. We are uncertain whether our findings could be repleted under controlled laboratory environment, or for learning that occur in immersive VR environments. Future studies may explore our research objective under those conditions and vary the duration of the VR intervention to explore the versatility of our findings. Additionally, we had relied on subjective-instruments to measure some of the variables of interest in this study. We also acknowledge that some of our scales had a low reliability. Future studies may explore the use of more objective assessment of students' cognitive processing and affective outcomes. Future studies may explore the use of eye-tracking devices and objective measures of cognitive processing and affective outcomes to obtain more objective data on student activities and emotional responses in VR.

Future research can investigate how various self-explanation prompts, and the sequence of – during or after the simulation – affect learning (Bisra et al., 2018). Additionally, we recommend that future studies examine the extent to which the quality of self-explanations students provide influences cognitive and affective learning outcomes in VR. Future studies may also explore the effects of other generative activities identified in the extant literature (i.e., drawing, mapping) on learning in VR. Finally, future studies may examine the direct and indirect relationships between cognitive processing, affective outcomes (such as presence, motivation, flow), and self-explanation activities on learning. Such studies may highlight the mechanisms at play when learners engage in self-explanations during or after VR activities. Furthermore, it can also help VR interventionists identify how to use self-explanation and other generative learning activities to facilitates VR learning.

4.6 CONCLUSIONS

This study adds to the current body of evidence in the research on the application of design and pedagogy principles in educational VR environments. Results for learning outcomes showed that exploratory or discovery-based VR did not improve declarative knowledge. However, guided or scaffolded VR interactions enhanced learning. We also found that follow VR learning up with generative activities – e.g., self-explanation – improved students' problem-solving skills, fostered triggered situational interest and self-efficacy beliefs in context of this study. Additionally, we observed that integrating self-explanation into VR activities reduced extraneous cognitive load and offloaded intrinsic load. These results have significant theoretical significance for future VR studies. Similarly, the findings observed in this study also have significant implication for how educators and instructional designers implement evidence-based principles of generative learning to engender desirable learning outcomes and enhance the VR learning experience. The result of the study provides evidence in support of the learning benefits of integrating generative activities into VR learning to optimize the VR learning experience.

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Table 4.1: Overview of the tested hypothesis in the study

Hypothesis	**Theoretical framework**	**Outcome Measure**	***Predictions for VR versus traditional instruction***
Deep Learning hypothesis	Cognitive theory of multimedia	Declarative knowledge (Phase 1)	1a: VR = CONTROL
		Declarative knowledge (Phase 2)	1b: VR > CONTROL
		Procedural knowledge	1c: VR > CONTROL
Generative hypothesis	Generative learning theory	Knowledge Application	2: VR + GA > CONTROL
Motivation hypothesis	Self-efficacy & Interest theory	Triggered Situational Interest	3a: VR + GA > CONTROL
		Maintained Situational Interest	3b: VR + GA > CONTROL
		Self-efficacy	3c: VR + GA > CONTROL
Cognitive hypothesis	Cognitive load theory	Extraneous cognitive load	4a: VR + GA < CONTROL
		Intrinsic cognitive load	4b: VR + GA < CONTROL
		Germane cognitive load	4c: VR + GA > CONTROL

Abbreviations: VR, Virtual Reality; GA, Generative activity

Table 4.2: Means, SDs and effect size results for declarative and procedural outcomes

Cognitive Learning Outcomes	***VR***		***Traditional Instruction***			
	M (EMM)*	*SD(SE*)*	*M (EMM*)*	*SD(SE*)*	*d [95% CI]*	η^2
Declarative knowledge (Phase 1)	6.58	3.22	5.89	2.47	0.24 [-0.39, 0.88]	0.01
Declarative knowledge (Phase 2)	8.68	2.67	7.05	2.51	0.63 [-0.02, 1.28]	0.09
Procedural Knowledge	6.75*	0.42*	4.46*	0.42*	1.29 [0.59, 1.98]	0.29

Note: Guidance scaffolds were provided to the VR group prior to phase 2

Table 4.3: Means, SDs and effect size results for knowledge application

Group	*M*	*SD*	Cohen *d* [95% CI]	*Eta-squared* (η^2)
VR+SE	8.47	2.59	0.97 [0.29,1.64]	0.2
Control	6.26	1.91		

Note: VR is Virtual Reality; SE is self-explanation generative activity

Table 4.4: Means, SDS, Effect sizes and Posterior prediction, and 95% confidence intervals for affective and cognitive processing outcomes. Results are obtained using a Robust Bayesian Estimation Method with unequal variances t-distribution model

Outcomes	**Type of Outcome**	***VR + Self-Explanation***		***Traditional Instruction***			
		M	*SD*	*M*	*SD*	*d*	$\beta_{\text{Posterior}}$ *[95% CI]*
Affective	Triggered Situational Interest	5.88	.59	5.26	1.16	0.67	.62 [-0.01, 1.25]
	Maintained Situational Interest	5.13	.64	4.8	1.37	0.31	.33 [-0.39, 1.05]
	Self-efficacy	5.97	.48	5.25	1.20	0.78	.73 [0.09, 1.35]
Cognitive Processing	Extraneous Load	2.93	.91	4.04	1.56	-0.86	-1.10 [-1.97, -0.24]
	Intrinsic Load	4.47	.72	5.84	1.02	-1.56	-1.37 [-1.97, -0.77]
	Germane Load	5.65	.55	5.89	.83	-0.34	-0.25 [-0.72, 0.23]

CHAPTER 5

SUMMARY AND CONCLUSION

The findings of the three studies described in this dissertation can provide empirical, theoretical, and practical insights into how to leverage the affordances of VRs to foster positive learning experiences and outcomes in different domains of engineering education.

5.1 Empirical Contributions

Several prior studies have focused on the design and pedagogical of effective learning in the traditional multi-media environment. However, very few studies have examined the design and pedagogical imperatives essential to harnessing the educational affordances of VR. Similarly, there has been a scant focus on how to translate evidence-based principles to harness these affordances, especially for engineering education. Hence, the studies described in this dissertation examined the application of theory-driven and evidence-based design and pedagogy principles for optimizing the educational benefits of VR, especially for learning in engineering contexts.

The first study of the dissertation presents a systematic review of the learning effects of evidence-based multi-media design and pedagogy principles in educational VR environments. The results of the review study highlight the effects of different evidence-based principles on learning in VR. Some of the principles observed in the studies reviewed produced a moderate-to-large effect on learning in VR media (e.g., the generative activities, pre-training, and modality principles). Additionally, the review study identified gaps in VR learning literature and proffer directions for future empirical research on the learning effects of VR contents that derive from evidence-based design and pedagogy principles of multimedia learning. The review study also highlights the factors that moderated the effect of different design and pedagogy principles on learning in VRLEs. Additionally, the review study showed that some of the evidence-based principles may have stronger effects on high-order learning tasks such as knowledge application and transfer, but not on declarative knowledge and knowledge retrieval. The study also identified emerging evidence-based principles that have not been previously associated with studies in the traditional multi-media literature.

The second dissertation study builds on the systematic review by focusing particularly on VR research in engineering education. This study assessed the state of VR research in engineering education to evaluate the role educational theories have played in engineering VR research studies. A systemic synthesis of 51 studies suggested that a majority of VR studies in engineering were usability studies. Furthermore, many of the studies lacked any underpinning theoretical or pedagogical framework. Based on these observations, the study makes a case more theory-driven and methodologically rigorous VR research in engineering education. The study also highlights some evidence-based principles that can guide engineering educators interested in research on VR and outlines potential directions for future VR research in engineering education.

The third dissertation study addresses some limitations identified in Studies I and II. The study examines the effects of scaffolding (a design feature) and self-explanation (a generative learning activity) on different cognitive and non-cognitive learning outcomes in an engineering VR context. The study included engineering students who were learning statics content in VR as participants. The study demonstrated that students who used VR did not do better compared than those in a control group on declarative knowledge tasks when the VR activity was not scaffolded. However, the study showed that students who learned in VR outperformed those who did not on a procedural knowledge task. Additionally, the study found that integrating a self-explanation task into VR learning activity significantly enhanced students' performance on a problem-solving task and fostered triggered situational and self-efficacy beliefs. The study also found that integrating a self-explanation– generative activity – in VR tasks reduced extrinsic and intrinsic cognitive processing.

5.2 Theoretical Contributions

The results of these dissertation studies have notable implications for cognitive, motivational, and generative learning theories that are relevant to designing VR to support learning. For instance, Study I found that the modality principles (replacing text and images with narration and images) have substantial learning benefits for learning in VR media. The dual-channel presentation hypothesis suggests that multimedia and VR lessons that leverage the auditory and visual processing channels (e.g., narration and images) will facilitate better assimilation of VR content than those contents that overload the visual processing channel. Study II implies that the perceptual realism of VRs can engender extraneous processing, which may cause disorientation or distract learners from the instructional objective.

Study III supports the deep learning hypothesis, which suggests that students who are guided in VR environments are likely to be better engaged with VR instructional activities. Additionally, Study III supported the generative activity hypothesis, which posits that generative activities enable students to select, organize, and integrate the most essential components of the instructional activity. Students who select, organize, and integrate relevant information may problem solve engineering concepts more effectively and efficiently. The study also demonstrated that adding self-explanation tasks to VR-based instruction can improve students' confidence in their abilities to comprehend and apply engineering principles to solving novel problems, which may be because learners' attentions are better drawn to instructional content than to the VR environment itself. Furthermore, Study III highlights the significance of generative learning activities for cognitive processing and load in educational VR environments. Past studies have portrayed generative learning activities only in light of their effects on generative processing that facilitate knowledge construction and sense-making. However, the findings of Studies I and III shows that generative activities may not only engender germane processes, but they could reduce extraneous load and offload intrinsic processing.

5.3 Practical Contributions

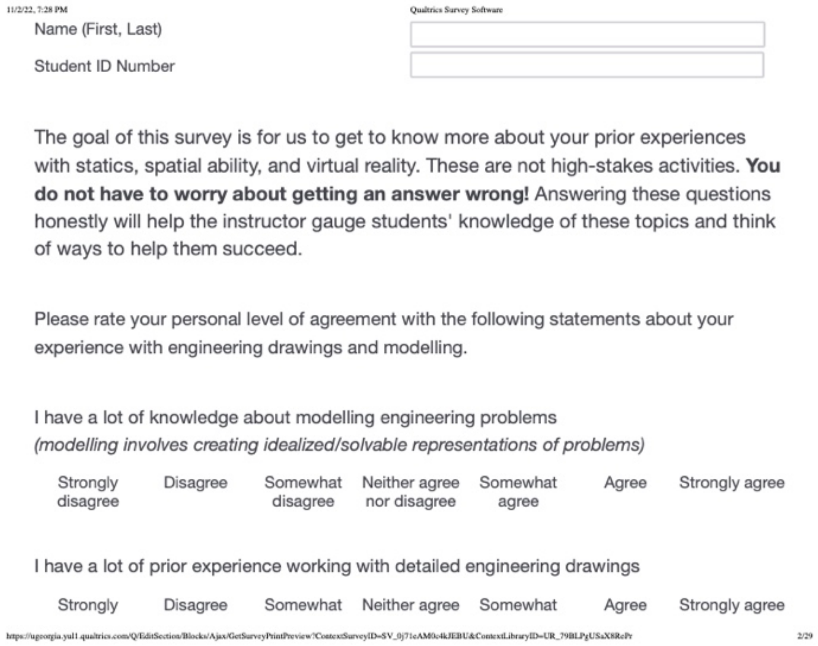
This dissertation highlights that there has been a growing interest in investigating the benefits of evidence-based principles of multi-media learning for learning in VR media. The first two studies support many of these evidence-based principles to facilitate design, pedagogy and learning in VRLEs. The third study provides empirical support for the learning effects of pedagogical principles to facilitate learning experiences in an under-explored area of VR research. Based on the major findings of these dissertation research studies, I outline the following considerations for designing and implementing VR environments that enhance cognitive processing, and the VR learning experience:

1. Drawing on the modality principle (learners can use both of their visual and auditory processing channels to process multimedia content), VR instructional design should prioritize the use of meaningful images with narrations over on-screen text to enhance the VR learning experience *(Modality principle)*
2. Using cues (e.g., arrows), annotations and visual highlights could help the learners identify the most important VR content *(Signaling principle).*

3. Guiding learners by using technological navigational aids or pedagogical guidance could reduce learner disorientation and minimize cognitive overload. Additionally, with high spatial content material and activities, visual scaffolds should be used instead of verbal scaffolds *(Scaffolding principle).*
4. Providing pre-training activities by familiarizing students to key concepts and terms before the VR activities can enhance VR learning experience *(Pre-training principles).*
5. Ensuring that all multi-media VR content, including animations, narrations and supporting contents are introduced sequentially and logically in order to assist the learner in managing the complexity of the activity could enhance VR learning experience *(Sequencing principle).*
6. Breaking VR activities into clear and meaningful segments or phases, rather than long and uninterrupted presentations, so learners can re-orient themselves with the learning objectives at each phase before moving on to the next phase will enhance the learning experience *(Segmenting principle).*
7. Using highly behavioral embodied agents can disorient and distract learners. Rather, the design of instructional VR should employ a less behaviorally and visually embodied agent that uses conversational languages. Learners respond better to VR instructional agents that they can relate to *(embodiment and personalization principles).*
8. Promoting collaborative learning that facilitates interaction between students and encourages learners to provide and receive feedback during the interactive process can enhance the VR learning experience *(collaborative principle).*
9. Highly immersive VR experiences may be unsuitable for learning in many learning contexts. Immersive VR experiences may be best used when the emphasis is on higher

learning outcomes (e.g., skills-training, procedural knowledge, or problem-solving activities).

10. Encouraging and prompting learners to engage in generative activities during or after the VR experience can enhance the learning process and promote positive learning outcomes. By engaging the generative activity, students select the most important aspects of the activities, organize in ways that facilitate understanding of the learning material. Learners can also better reflect on their experience and apply what they have learned to their prior knowledge when they engage in generative learning activities *(Generative activity principle)*.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Qualtrics Survey Software

Name (First, Last)	
Student ID Number	

The goal of this survey is for us to get to know more about your prior experiences with statics, spatial ability, and virtual reality. These are not high-stakes activities. **You do not have to worry about getting an answer wrong!** Answering these questions honestly will help the instructor gauge students' knowledge of these topics and think of ways to help them succeed.

Please rate your personal level of agreement with the following statements about your experience with engineering drawings and modelling.

I have a lot of knowledge about modelling engineering problems
(modelling involves creating idealized/solvable representations of problems)

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

I have a lot of prior experience working with detailed engineering drawings

Strongly	Disagree	Somewhat	Neither agree	Somewhat	Agree	Strongly agree

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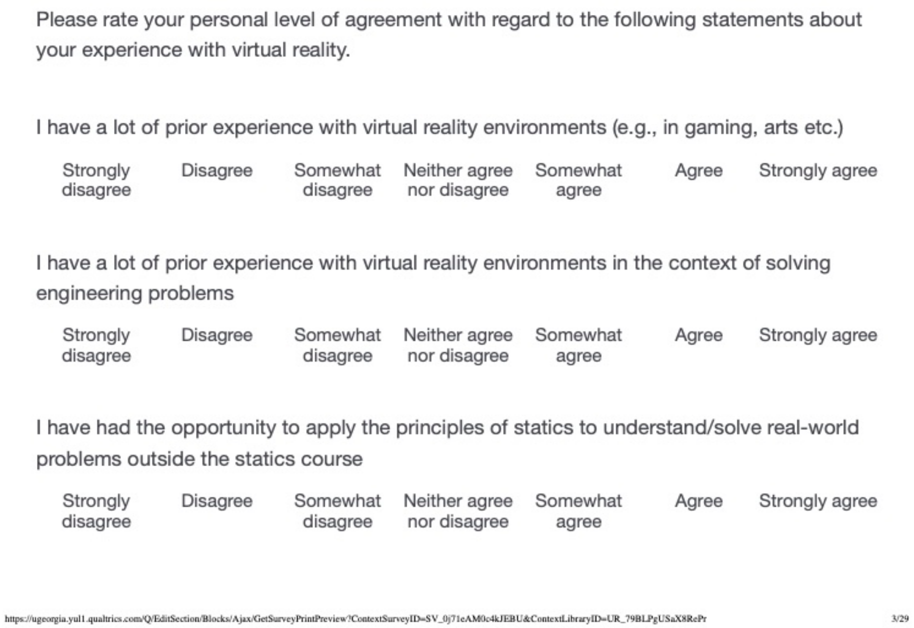

Please rate your personal level of agreement with regard to the following statements about your experience with virtual reality.

I have a lot of prior experience with virtual reality environments (e.g., in gaming, arts etc.)

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

I have a lot of prior experience with virtual reality environments in the context of solving engineering problems

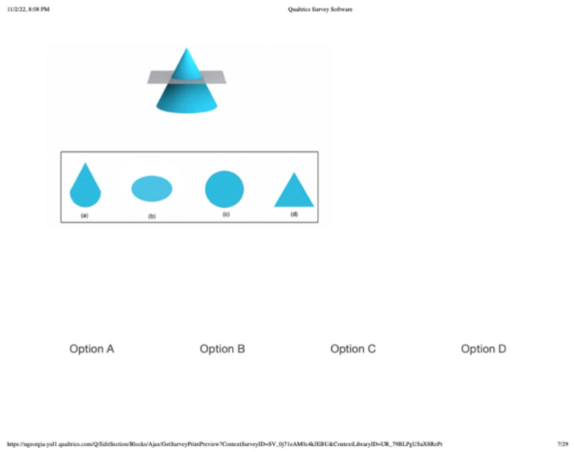
Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

I have had the opportunity to apply the principles of statics to understand/solve real-world problems outside the statics course

Strongly disagree	Disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Agree	Strongly agree

https://ugeorgia.yul1.qualtrics.com/Q/EditSection/Blocks/Ajax/GetSurveyPrintPreview?ContextSurveyID=SV_0j71eAM0c4kJEBU&ContextLibraryID=UR_79BLPgUSaX8RePr 3/29

Appendix A: Pre-activity measures of prior knowledge and virtual experience in Qualtrics platform



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Option A Option B Option C Option D

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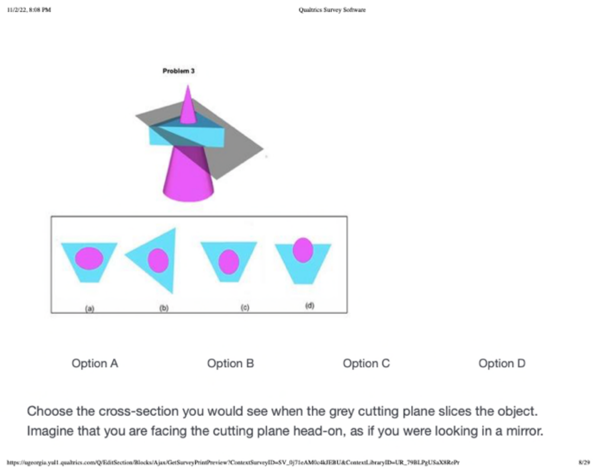

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Option A Option B Option C Option D

Choose the cross-section you would see when the grey cutting plane slices the object.
Imagine that you are facing the cutting plane head-on, as if you were looking in a mirror.

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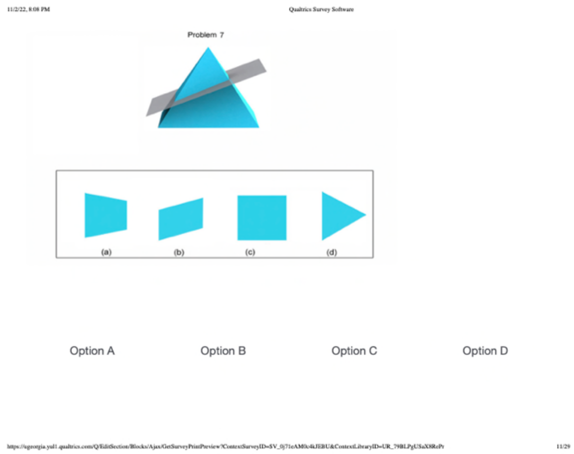

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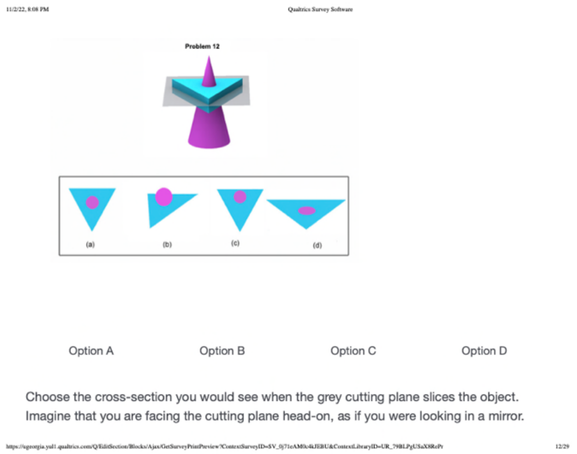

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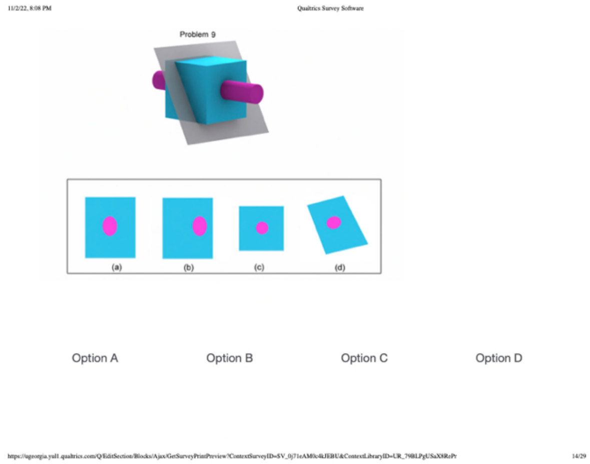

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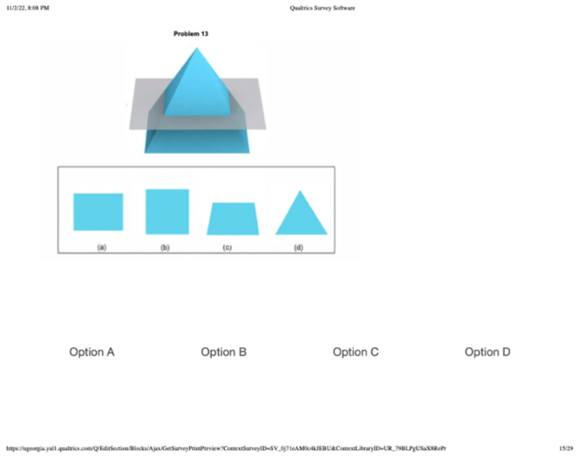

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Appendix B: Sample of Santa-Barbara Solids Test on Qualtrics platform

Appendix C: Self-Explanation – generative activity– prompts for students who learned with VR

By now, you should have completed Phase I and II of the statics project involving the mini hydraulic excavator. This exercise is designed to make you reflect on the steps you took for Phase I/II and think of the steps you need to take to complete Phase III.

Please use the prompts provided below to explain the steps and reasoning as if you were explaining them to a friend.

Please ensure that you complete this exercise by yourself (individually).

List and explain the steps you took in creating the simplified model and in identifying/measuring the dimensions necessary to answer questions Q1, Q2, Q3 posed in the project

List and explain the steps you took in creating the simplified model and in identifying/measuring the dimensions necessary to answer questions Q1, Q2, Q3 posed in the project

List and explain the steps you took in creating the simplified model and in identifying/measuring the dimensions necessary to answer questions Q1, Q2, Q3 posed in the project

Please explain in your own words how using virtual reality environment helped you in obtaining the dimensions required to answer Q1, Q2, Q3 posed in the project

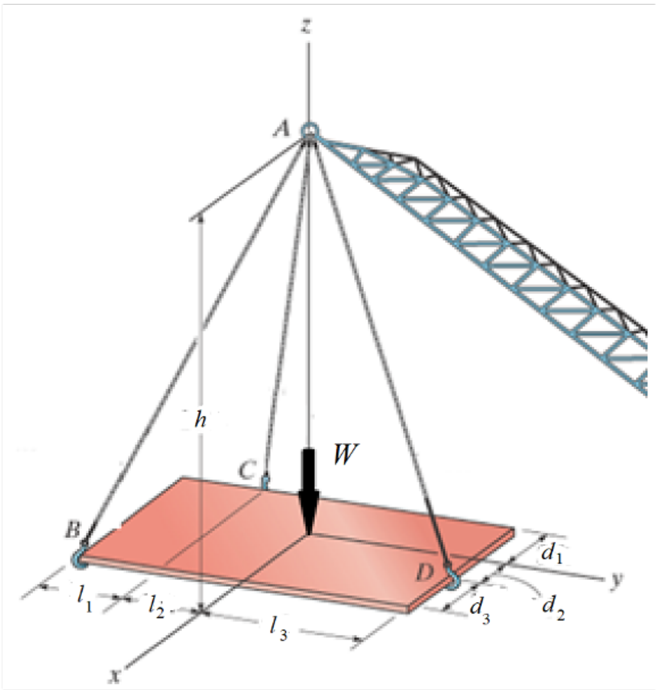
Imagine you have to teach your fellow students. How would you explain why the above listen static principles are needed in answering Q1, Q3, Q3 posed in the project.

Appendix D: Affective and cognitive measures using in Study III

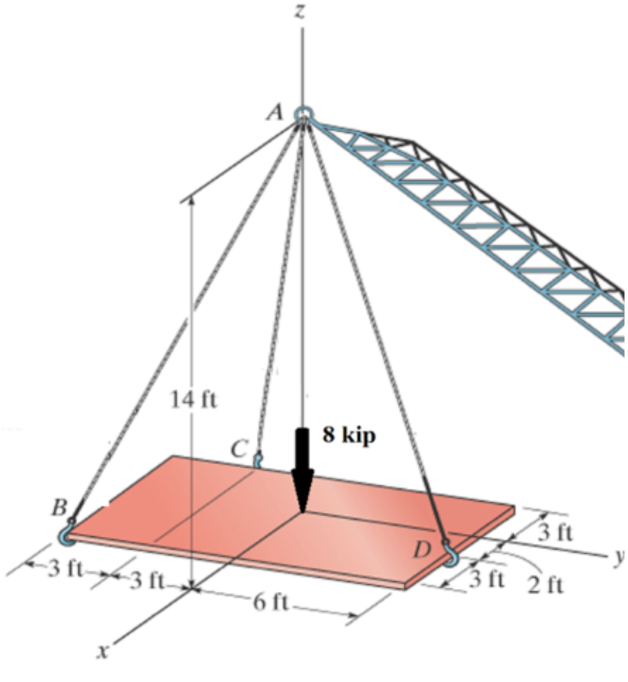
Outcomes	Questions
Triggered Situational Interest	I want to be able to concentrate on the excavator project
	I think the excavator project was interesting
	The excavator project appealed to me
	I felt bored with the excavator project
Maintained Situational Interest	I find important knowledge in the excavator project
	I think what I did in the excavator project is important
	I find this excavator project personally meaningful
	The excavator project was so interesting that I would have continued working on it even if an interruption occurred
	What I experienced in the excavator project is closely related to my future life/study
Self-efficacy	As a result of this excavator project, I am confident that I can understand the basic concepts of statics
	As a result of this excavator project, I am confident that I understand the advanced/complex concepts of statics
	As a result of this excavator project, I am confident that I can perform well on other engineering learning activities

Outcomes	Questions
Self-efficacy	As a result of this excavator project, I am confident that I can do well in this statics course
	As a result of this excavator project, I am confident that I can explain the surveying concepts I learned to another person
	As a result of this excavator project, I am confident that I can master the engineering skills learned in this course
Extraneous cognitive load	During this excavator project, it was exhaustion to find the important information
	The design of the excavator project was very inconvenient for learning
	During this excavator project, it was difficult to recognize and link crucial information
Intrinsic cognitive load	For this excavator project, many things needed to be kept in mind simultaneously
	The excavator project was very complex
Germane cognitive load	I made an effort, not only to understand several details, but to understand the overall context of this excavator project
	My point when dealing with excavator project was to understand everything correctly
	My point when dealing with excavator project was to understand everything correctly

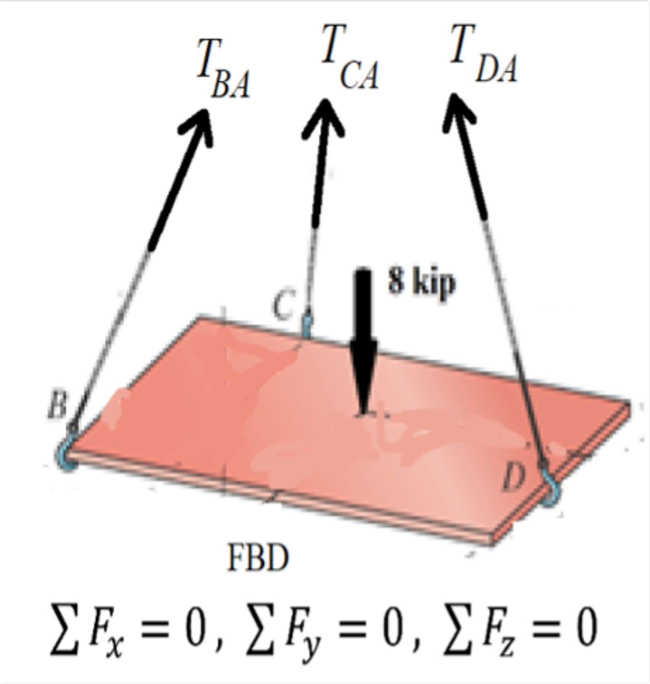
Appendix E.1: Real-world problem



Appendix E.2: Modelling the problem



Appendix E.3: Estimating the problem



Appendix E:4 Problem-solving phase