Teaching with CAVE virtual reality systems:
Instructional design strategies that promote adequate cognitive load for learners

By

Leah T. Ritz

Plan B Project

Submitted in partial fulfillment of the requirements
for the degree of Masters in Science in Natural Science/Mathematics
in the Science and Mathematics Teaching Center of the
University of Wyoming, 2015

Laramie, Wyoming

Masters Committee:

Associate Professor Alan Buss, Chair
Assistant Professor Tonia Dousay
Associate Professor Ruben Gamboa

Abstract

This research uses the framework of Cognitive Load Theory to inform changing trends in instructional design for teaching with an emerging technology, specifically an immersive virtual reality (IVR) system known as Cave Automatic Virtual Environment (CAVE). By highlighting the affordances of IVR specific to the CAVE and how they can impact the three domains of cognitive load, this research will identify how immersive CAVE technology can alter cognitive load to promote or deter deeper learning. It will also underline the importance of establishing new instructional strategy guidelines for this emerging educational technology to mitigate the risk of designing lessons with CAVEs that simply overwhelm the extraneous cognitive load with unnecessary information and impede the working memory resources of learners. The literature review focuses on how use of the CAVE as an educational tool will positively and negatively impact a learner's cognitive load, as well as current pedagogy and practices for educational technology. This background information will then be applied to make recommendations for best practices in designing lessons and instructional materials for the CAVE to support adequate cognitive load and create opportunities for positive learning. The recommendations are in the areas of content, differentiated instruction, interactivity of instruction, presentation of learning materials, virtual and physical spaces, and technical knowledge.

Table of Contents

Chapter 1

Introduction

Context for Research

Technology is firmly entrenched in all manner of day-to-day operations in the 21st century including in the field of education where it supports a wide range of learning activities (Winn, 2002). Instructional designers have long been utilizing a variety of educational technologies to enhance the classroom experience and promote deeper learning (Mikropoulos & Natsis, 2011; Sweller, 2008) because they make available a number of instructional strategies that were inaccessible or unusable without technology (Crosier, Cobb, & Wilson, 2002; Dalgarno & Lee, 2010; Winn, 2002). Technological advances in the classroom have allowed educators to deliver more accurate information to their students more easily (Bamford, 2011; Keengwe & Onchwari, 2011; Sweller, 2008). However the role of technology is not to assume that of a teacher because teachers must still interpret what is shared with the technology (Bamford, 2011; Keengwe & Onchwari, 2011), and they should be supported in their ability to effectively use technology for this end (Keengwe & Onchwari, 2011).

One of the latest evolutions in educational technology is 3-dimensional (3D) visualization with virtual reality. Virtual reality (VR) is a technology that uses computer graphics to simulate or replicate an environment, often using sensory stimuli (visual, auditory, tactile, etc.) to lead users to perceive an artificial environment as real (Blascovich & Bailenson, 2005). It can take many forms ranging from simple computer graphics of 3-dimensional shapes to highly interactive, fully immersive, multisensory environments in a laboratory. The latter type of virtual reality is commonly referred to as immersive virtual reality (IVR). VR experiences are varied and can be passive allowing users to watch as simulations pass by (Bamford, 2011), or they can be dynamic letting users interact with representations of real objects by manipulating and rotating them to different orientations with a handheld device (Blascovich & Bailenson, 2005; Lee & Wong, 2014).

Since the 1980s and 1990s, educators and researchers alike have noted the potential of VR in education (Dalgarno & Lee, 2010; Mikropoulos & Natsis, 2011; Pivec, 2007). However, Crosier et al. (2002) noted that very few researchers have attempted using VR for educational applications with even fewer actually using it and evaluating it in the classroom. Since the mid-2000s, there has been a resurgence of interest in using virtual environments as educational tools (Merchant, Goetz, Cifuentes, Keeney-Kennicutt, & Davis, 2014) because educators have recognized that innovative approaches in teaching with technology have been able to create more effective learning environments (Keengwe & Onchwari, 2011; Merchant et al., 2014).

Statement of the Problem

Virtual reality is still an emerging technology and there are a number of unknowns in terms of how it can alter student cognitive processes and be used as an effective teaching tool to augment learning (Dunleavy, 2009; Hew & Cheung, 2010). Researchers are beginning to explore the impact virtual reality has on learners and the changes it would require in pedagogy (Hew & Cheung, 2010), and remaining concerns about the efficacy of VR for teaching have more to do with the pedagogy than the tools themselves (Finkelstein et al., 2005). In the past, educational technology research has focused more often on the technology than on learners' needs (Lau & Lee, 2012; Lim & Tay, 2010; Pivec, 2007), but the extent to which emerging educational technology like VR and IVR will be viable depends on how well their adopters take into account current understandings of human cognition and the methods in which students learn as described by Cognitive Load Theory (Sweller, 2008). Simply using new technology because it is available is inexcusable (Sweller, 2008), and successful instruction using VR requires the technology be incorporated in well-designed contexts that apply theoretical cognitive approaches to accomplishing objectives (Mikropoulos & Natsis, 2011). Conversely, if teachers are not equipped with the right pedagogical skills and knowledge to integrate technology into instruction using technology will continue to be ineffective (Hew & Brush, 2007; Keengwe & Onchwari, 2011).

While there is educational research reporting on the efficacy of VR as a classroom teaching aid (Merchant et al., 2014), there is limited research on immersive virtual reality as an educational tool, and even less information for instructors on how to effectively design lessons to integrate immersive virtual educational technology in curriculum. As Winn (2002) notes, the challenge lies in trying to keep up with how educational technology changes and how it will change pedagogy. While Dede (2009) reminds readers that “further studies are needed ... on the instructional designs best suited to each type of immersive medium, and on the learning strengths and preferences [that] use of these media develops in users” (p. 68).

This paper adds to the literature by filling in a remaining gap on instructional design with technology by proposing guidelines for best practices in the integration of immersive virtual reality, particularly CAVEs, in instruction. Furthermore, the guidelines will meet a practical need by informing and supporting educators as they adapt instructional design for emerging technology to capitalize on the unique technological characteristics of immersive virtual reality. The outcome of this research can be used to assist educators as they adopt and effectively integrate emerging educational technology as a teaching tool, and it will also recommend further studies in the areas of cognitive load of learners and immersive virtual technology.

Research Question and Methods

The concept for this research stems from informal observations as an educator using a type of IVR known as the CAVE to teach K-12 students, as well as an investigation of literature on instructional design for virtual reality that indicated a lack of information and potential for more in-depth discussion. A survey of the literature indicates that Cognitive Load Theory provides guidelines for instructional designers to promote increased learning through appropriately designed lessons (Meissner & Bogner, 2013; Sweller, 2008), and that instructional strategies exist for teaching with technology (Dickey, 2005; Winn, 2002). However each technology has different qualities that make them effective tools for their intended purpose (Dalgarno & Lee, 2010; Windschitl & Winn, 2000). CAVEs are an emerging virtual reality technology with attributes that make them well suited for teaching 3D concepts (Mikropoulos & Natsis, 2011). Yet in terms of educational virtual technology, CAVEs are so new that little is understood about how they could affect student cognitive load and subsequent learning (Lee & Wong, 2014). Absent from the literature, however, are any apparent guidelines for how to best use VR, especially CAVEs, as educational tools.

Recognizing the gap in the literature as outlined above and understanding the need for more appropriate practical guidelines, the research question being investigated is: How can instructional design strategies for technology be adapted to facilitate learning through adequate cognitive load in CAVE IVR? The primary methodology is a literature review that uses three frameworks to address the question. The first framework is conceptual and focuses on understanding virtual reality technology, its affordances, and its efficacy in the field of education. The second framework is theoretical and applies Cognitive Load Theory as a tool for understanding how virtual reality may impact learners in ways that are atypical from a standard classroom. It also helps address how virtual reality can add to or detract from learning experiences in the CAVE. The last framework is practical and identifies some of the current pedagogy and practices that are best suited for teaching with multimedia technology and how they can be adapted to teaching with virtual reality. The literature discussed in each framework will be synthesized to propose a list of guidelines for teaching with the CAVE, hypotheses on how the guidelines promote sufficient cognitive load, and recommendations for how to check that lessons have been intentionally designed to incorporate these instructional design guidelines. As an end result, the guidelines will be applied to an example lesson plan that could be used in the CAVE.

Chapter 2

Literature Review

Conceptual Framework: Virtual Reality, Affordances, and Education

In general, use of technology in a classroom can help improve students' test scores, inventive thinking, and overall motivation (Hew & Brush, 2007). Educators today use a number of instructional technologies like computer animations and videos, but typically, such technologies are quite passive consisting of frames of images that move at a pace outside of the user's control much like a movie. Information can disappear before a learner has had time to adequately process it, necessitating that learners hold content in their minds while integrating it with information presented at other times in the animation (Ayres & Paas, 2012).

However, VR is distinctly different from other multimedia because it is more interactive and can often be controlled by the user. Because of this, educators see potential for VR as an educational tool and are putting great effort into developing the technology for that purpose (Chen, Toh, & Wan, 2004; Dalgarno & Lee, 2010). Many attributes of VR technology may actually be of benefit to education (Crosier et al., 2002), and VR is predicted to cause significant technological transformation in educational media (Chen, Toh, & Wan, 2004). There is a growing body of research supporting VR as an important emerging educational technology (Hew & Cheung, 2010; Merchant et al., 2014) with an increasing number of case studies demonstrating the ability of 3-dimensional VR instruction to create positive learning outcomes when compared with control groups taught in 2-dimensions (2D) in a traditional classroom (Ketelhut & Nelson, 2010; Merchant et al., 2014).

Despite the seeming relationship between educational technology usage and student achievement, the technology itself does not directly cause learning (Winn, 2002). Instead, technology provides affordances that help facilitate learning. Affordances are essentially emergent properties of the technology, or actions made possible merely because of the availability of a tool (Dalgarno & Lee, 2010). Virtual reality is a unique technology, and as such creates a number of distinct affordances that could be capitalized on by classroom teachers to enrich learning opportunities (Merchant et al., 2014). Affordances of VR include the ability to assume multiple perspectives, contextual learning, and transfer of knowledge and skills to real-world situations (Mikropoulos & Natsis, 2011). These particular affordances of VR make it possible for the technology to facilitate tasks that lead to enhanced representation of spatial knowledge, greater opportunities for experiential learning, increased motivation and engagement, and richer more effective collaborative learning as compared to 2D alternatives (Dalgarno & Lee, 2010).

As a learning tool, VR is able to situate students in contexts and relationships not achievable in traditional learning environments (Bailenson et al., 2008) by making the invisible visible or allowing students to participate in activities that would otherwise be impossible in the real-world like traveling around Mars or touring a castle in the Middle Ages (Dalgarno & Lee, 2010; Lau & Lee, 2012). The significance of the affordances of improved visualization through multiple perspectives is a recurring theme in the literature on VR because the ability to assume multiple points of view of the same dataset or scenario helps users make sense out of complex information with detailed 3-dimensional images (Bailenson et al., 2008; Crosier, Cobb, & Wilson, 2002; Dalgarno & Lee, 2010; Hinze et al., 2013; Höffler & Leutner, 2011; Huk, 2006; Lee & Wong, 2014; Limniou, Roberts, & Papadopoulos, 2008).

Virtual reality and spatial visualization. Educational researchers have noted VR's exceptional potential in the area of Science, Technology, Engineering, and Math (STEM) education (Hinze et al., 2013) because the technology is particularly well suited for teaching 3D spatial concepts (Mikropoulos & Natsis, 2011). STEM classes often require students to conceptualize intangibly large (e.g. astronomic or geologic scale) or small (e.g. nanoscale) concepts that are nearly invisible in the physical world (Hinze et al., 2013). Examples of these types of concepts include molecular interactions, physical relationships between objects in which energy is transferred, wave properties of sound and light, crystallization of minerals, plate tectonics, and many concepts on incredibly small, micro-levels or large, macro-levels (Next generation science standards: For states, by states, 2013). A benefit of 3D visualization with VR is that instructors can narrow these broad concepts to the content they want to focus on and show it at appropriate scales for students while still maintaining the structural integrity and real life quality of the object in three dimensions (Finkelstein et al., 2005; Winn, 2002).

In order for students to interact with this type of content and meaningfully participate in STEM classes, they must utilize their cognitive powers of spatial visualization, or the ability to imagine objects, mentally rotate interacting parts, and organize them as in a puzzle (Hinze et al., 2013; Höffler & Leutner, 2011; Huk, 2006). A student's likelihood for success in STEM classes is positively related to his or her ability to think about concepts spatially (Hinze et al., 2013). Spatial visualization is a function of a student's working memory and those who have low spatial ability tend to have fewer cognitive resources available for processing 3D spatial images, making STEM classes more challenging (Lee & Wong, 2014). Consequently, students with high spatial abilities who can readily imagine and manipulate objects often outperform students with low spatial abilities in STEM classes (Hinze et al., 2013).

Interestingly, recent research has shown that VR can help students visualize in 3D by compensating for lack of spatial visualization skills (Höffler & Leutner, 2011; Lee & Wong, 2014), thereby enhancing students' abilities to process and understand more complex concepts (Lee & Wong, 2014). In the function of an ability-as-compensator tool, VR supports students with low spatial abilities in successfully using 3D models to make up for their decreased ability to mentally rotate and manipulate models presented two-dimensionally (Höffler & Leutner, 2011; Huk, 2006; Lee & Wong, 2014). Lee & Wong (2014) propose the ability-as-compensator benefit of VR can be explained by cognitive theories in that virtual reality instruction can help to reduce unnecessary cognitive load and increase learners' ability to access stored working memory resources by engaging learners in active processing of instructional material.

Some researchers posit that the 3D visualization affordance of VR might be most useful for low spatial ability students (Lee & Wong, 2014), but instructors must be conscious of the cognitive load that could be imposed on their students by using VR (Huk, 2006). Huk (2006) showed low spatial ability students preferred to use 2D models as opposed to 3D models, possibly because they were cognitively overloaded by the 3D visualizations, indicating that instructors hoping to utilize the ability-as-compensator role of VR must be wary of other cognitive load factors.

Other researchers have discovered the capacity of VR to bolster the abilities of naturally high spatial ability students (Höffler & Leutner, 2011). VR can also assume the role of ability-as-enhancer, allowing students with high spatial ability to perform at an advanced level by augmenting their innate ability to manipulate mental models (Höffler & Leutner, 2011; Huk, 2006). High spatial ability users seem to be drawn to 3D visualizations because with an already elevated spatial ability, the visualizations do not induce any higher cognitive load (Huk, 2006). Because of this VR may best assist high spatial ability students when the inherent complexity of a task is very high (Lee & Wong, 2014). Support for the ability-as-enhancer theory comes from studies that show multimedia tools like VR seem to have the greatest results for students with low prior knowledge but high spatial ability (Mayer, 1997).

Educators in a variety of fields have been able to successfully enhance student learning of spatial concepts in chemistry, cell biology, physics, environmental science, marine ecology, geology, astronomy, and a number of other science content areas by utilizing the affordance of 3D visualization provided by VR (Finkelstein et al., 2005; Hinze et al., 2013; Huk, 2006; Limniou et al., 2008; Merchant et al., 2014; Mikropoulos & Natsis, 2011), thus indicating that VR has potential to assist students with different spatial abilities to improve overall performance on spatial visualization tasks.

Immersive virtual reality: CAVE. Virtual reality is a broad category of technology, but the VR of interest in this research is a type of immersive virtual reality (IVR). Unlike VR, IVR environments create a “psychological state in which the individual perceives himself or herself as existing within, being immersed in, or having presence in it” (Blascovich & Bailenson, 2005, p. 230). The sensation of presence from immersion in the virtual environment is one of the biggest differentiating factors between IVR and more familiar types of VR like 3D movies, desktop 3D simulations, or 3D video games and is facilitated by the physical design of the IVR system. IVR setups usually provide the user with a wide field of view (80 degrees or more) in a virtual environment made of high resolution images projected in stereoscopy, or as two distinct images that overlap into one 3D image when the user wears a special headset. Additionally, the user is often motion-tracked to allow the environment to respond to his or her movements. A shorter delay period between user movement and virtual feedback adds to the feeling of physical presence in the environment as the environment seems to respond to user movements in real-time despite the fact that it is artificial (Blascovich & Bailenson, 2005).

There are an increasing number of IVR systems on the consumer market including head-mounted virtual reality equipment, but the one being assessed for educational potential in this research is the Cave Automatic Virtual Environment (CAVE). CAVEs vary in dimensions, but a typical CAVE is a four-walled room with three walls and a floor, 10 feet wide, 10 feet tall, and 10 feet deep (Mechdyne Corporation, 2012). Each surface is illuminated by computer generated objects and scenarios observed as two slightly offset images. Special glasses cause the images to overlap giving the effect of three dimensionality and simulating the natural way human eyes see objects stereoscopically (Baños et al., 2008) thus fooling the senses into thinking they are actually inside of a real, physical environment (Blascovich & Bailenson, 2005).

Use of 3D images, tracking of users, and coverage of a wide field of view are characteristics common across many types of IVR, but CAVEs are unique in the realm of IVR because of the ability users have to walk into and move around the space, unhindered by anything but the confines of walls. Because users have the full ability of their body to walk around and interact with their environment, behavior in the CAVE more closely mimics that in the real-world (Blascovich & Bailenson, 2005; Dunleavy, 2009). Additionally, the way CAVEs create digitally simulated virtual environments is somewhat analogous to the way artificial environments in the concrete, walled, physical world are built (Blascovich & Bailenson, 2005). Projections on the walls of the CAVE are backlit to help eliminate shadows on the walls thus enhancing the feeling of immersion in an environment. One user wears head-tracked glasses and uses some form of haptic control to interact with projected simulations. In the upper corners of the CAVE are infrared detectors that constantly send and receive information on the location of the user wearing the tracked glasses. A computer synchronizes and drives the projectors using the location information so that as the user interacts with the environment, the movements are recorded and the projected environment responds according to the user's new perspective (Mechdyne Corporation, 2012) thus giving a sensation similar to what would happen when perspectives change in a normal, non-artificial environment (Blascovich & Bailenson, 2005).

Like other types of VR, CAVE IVR has a number of affordances that could be of benefit to education and may create potential learning opportunities that were previously unavailable through non-immersive VR (Dede, 2009). The affordance most unique to the CAVE is that of presence, or a user's sense of being in and participating in an environment (Blascovich & Bailenson, 2005; Dalgarno & Lee, 2010; Mikropoulos & Natsis, 2011; Schifter, Ketelhut, & Nelson, 2012). In the past, the effectiveness of IVR has been measured by its ability to create presence (Bailenson et al., 2008), which has been shown to have positive impacts on learners (Limniou et al., 2008).

Users of VR often report increased sense of presence when using the technology (Bailenson et al., 2008; Baños et al., 2008;), but users of IVR technology like the CAVE comment that it offers different experiences than interacting with standard 3D or other VR applications on desktop computers or gaming consoles (Bowman, Bowman, McMahan, & McMahan, 2007). CAVEs, by virtue of being immersive, potentially have the power to heighten the sense of presence more than other VR delivery system because of the intense full body experience elicited by physically walking into and interacting with the environment (Bailenson et al., 2008; Blascovich & Bailenson, 2005; Limniou et al., 2008). The benefit of IVR over standard VR can be extrapolated from research on video game players that shows a heightened sense of presence in game contexts causes users to become more actively engaged in the virtual environment (Dickey, 2005). In terms of education, increased engagement can lead to improved opportunities for learning (Bailenson et al., 2008; Dalgarno & Lee, 2010; Dickey, 2005).

Even more beneficial for learning environments is that IVR allows users to interact with their surroundings first-hand (Blascovich & Bailenson, 2005). Rather than reading information, learners are actually experiencing it (Hew & Cheung, 2010), which may lead to better conceptual understanding (Dickey, 2005). Research is still uncovering exactly how immersion can impact learning (Dunleavy, 2009; Hew & Brush, 2007), but some studies are "demonstrating that when students actually experience learning material in an interactive video game context, they learn in unique manners" (Bailenson et al., 2008, p. 109). In general, while research has observed a relationship between improved student learning and use of VR, the mechanism for such results is uncertain (Blascovich & Bailenson, 2005). Better understanding of how students learn as well as how immersion in the CAVE affects learning will help identify instructional design strategies to support engaged, first-person learning opportunities.

Theoretical Framework: Cognitive Load Theory

Technology is ever advancing (Sweller, 2008), and is changing the way that educators teach (Keengwe & Onchwari, 2011). Too often, educational technology is used without knowing why or how it should best be implemented (Winn, 2002). The cognitive processes in the brain remain constant, but our understanding of those processes continues to advance and should inform pedagogy (Sweller, 2008). As a result, instructional designs change with better understandings of how students learn and as new educational technology becomes available (Winn, 2002). Cognitive Load Theory (CLT) provides the link between technology and cognitive theory by suggesting the "architecture of the human brain should be central in determining which technologies should be adopted and how they should be used" (Sweller, 2008, p. 32). CLT is the framework that will be used for understanding why and how VR, specifically IVR, can augment student learning when used in an educational context.

Introduced in the late 1980s, CLT was developed out of research on student problem-solving processes and adds to our understanding of how students learn and under what conditions learning may be the greatest (Sweller, 1988). The term cognitive load refers to the total amount of mental effort being used by the working memory (Ayres & Paas, 2012) and can be broken down into three types of cognitive loads: 1) the intrinsic cognitive load, which depends on the inherent difficulty and complexity of a task; 2) the extraneous cognitive load, which results from instructional design; and 3) the germane cognitive load, which derives from the amount of cognitive or working memory resources that the learner devotes to dealing with the intrinsic cognitive load (Meissner & Bogner, 2013; Sweller, 2008). These cognitive loads are additive and brains are simultaneously processing in all three (Sweller et al., 2003).

CLT is quite revealing for instructional design in that it suggests learning, defined as the formation and storage of new knowledge, or a change in long-term memory (Sweller, 2005), happens best under conditions that are aligned with an individual's cognitive ability (Chandler & Sweller, 1991; Sweller, 2005). Too much cognitive load imposed by poor instructional design or overly complex material will compromise learning because insufficient working memory resources are available to be devoted for processing new information (Ayres & Paas, 2012). The theory is best applied in practice to the area of instructional design for material that is cognitively complex or technically challenging (Chandler & Sweller, 1991; Meissner & Bogner, 2013). In order to facilitate the greatest amount of learning, instructional designers must provide adequate levels of intrinsic cognitive load, reduce extraneous cognitive load, and enhance germane cognitive load (Meissner & Bogner, 2013). CLT has been effective for identifying impediments to learning (Ayres & Paas, 2012), and a number of educational researchers have made recommendations on how to adjust lessons to accommodate for requirements in each cognitive domain (Ayres & Paas, 2012; Lee & Wong, 2014; Meissner & Bogner, 2013; Sweller, 2008).

Intrinsic cognitive load. The first domain, intrinsic cognitive load, derives from each task and is defined as the inherent effort associated with a specific task, depending on the difficulty and complexity of the task (Meissner & Bogner, 2013; Sweller, 1988). For example, the question, "What is 1 + 2?" has a relatively low intrinsic cognitive load for a high school student who has learned and stored processes, or schema, for answering that question. However, that same student may have a much higher intrinsic cognitive load if asked to solve a differential equation because he or she may not yet have the schema or mental processes to solve the problem.

Intrinsic cognitive load cannot be changed because it is part of the problem, and the ability to solve the problem, therefore, relies on existing schema, or information already stored by the student and mental processes for recalling and solving the task (de Jong, 2009). Despite being unable to change intrinsic cognitive load, CLT suggests that breaking the concept or task down into component parts, or sub-schemas, can function to simplify the task and make high intrinsic cognitive load tasks more manageable (Lee & Wong, 2014). Additionally, organizing instructional material from simple to complex can help control intrinsic load because learners do not initially experience the full complexity of the content (van Merriënboer, Kester, & Paas, 2006; van Merriënboer, Schuurman, De Croock, & Paas, 2002). Alternatively, information can be presented as a complete, complex unit, but learners' attention can be focused on subsets of interacting parts at different times (van Merriënboer, Kester, & Paas, 2006).

Extraneous cognitive load. The second domain, extraneous cognitive load, derives from instructional design itself and is the load caused by parts of instruction that are unnecessary for learning new material (de Jong, 2009; Sweller, 1988). It is heavily influenced by the way information or tasks are presented to the learner, especially if he or she is asked to interpret and integrate two or more sets of information before applying them for problem solving (Meissner & Bogner, 2013). It can frequently be avoided with a different instructional design (de Jong, 2009).

Instructional materials that frequently cause undue extraneous cognitive load are instructions or handouts that include diagrams. Often diagrams contain pictorial as well as written information. Before proceeding with a task, students must interpret the picture, hold the visual information in their memories, interpret the text and then mentally integrate the verbal and visual sets of information (Mayer, 1997). Human cognitive processes can only work through so much information at once, typically no more than three to four things at a time (Sweller, 2008). Depending on how new to the student the information on the diagram is, processing two sets of information at once can be quite taxing on cognitive resources and therefore impede learning. A strategy that has been shown to reduce extraneous cognitive load for this example is to place text next to pictures so that it is easier to hold all of the information in working memory at one time (Mayer, 2002; Sweller, 2008). The goal of instructional designers should be to reduce extraneous cognitive load, especially if tasks have a naturally high intrinsic cognitive load (Lee & Wong, 2014).

A second common source of extraneous load comes from lesson plans that call for students to solve problems for which they have no existing schema (high intrinsic cognitive load with low germane cognitive load). This can be mitigated in instructional design by presenting learners with worked out problems (de Jong, 2009). A third design strategy can alleviate extraneous load and by allowing students to use more cognitive capacity if visual and auditory parts of working memory are addressed at the same time (Mayer, 1997). Students may learn more efficiently if instructional material is presented as a combination of visual and auditory material (de Jong, 2009; Mayer, 1997; Robinson, 2004).

Germane cognitive load. The third domain of cognitive load, germane, is related to the working memory resources a learner has to devote to the information or task. Working memory serves to create a permanent store of knowledge, or schema. A schema is an organized pattern of thought or behavior that arranges categories of information and the relationships among them (Sweller, 1988). The working memory is also able to recall stored schema and process new information in terms of the already stored knowledge. For example, a person who is reading can make sense of text because of his or her stored schema. That person uses multiple schema to help recall that combinations of words form sentences, combinations of letters form words, and combinations of squiggles make up each letter. In terms of instructional design, the goal is to enhance germane cognitive load so learners can put more resources toward evoking existing schema, processing information, and attaching it to schema that will store it in long-term memory (Meissner & Bogner, 2013; Sweller, 2008). Research has indicated that germane cognitive load may be enhanced by increasing variability within instruction, which serves to improve engagement and motivation (Meissner & Bogner, 2013). More engaged students have a greater likelihood of tapping farther into their working memory for cognitive resources that will assist them in completing a task (Dickey, 2005).

Germane cognitive load seems to have an inverse relationship with extraneous cognitive load in that high extraneous load decreases germane load as a result of mental resources getting tied up by the processing of unnecessary information (de Jong, 2009). Sweller (2005) notes that in the past the majority of work within the CLT framework has been concerned with reducing extraneous cognitive load to permit an increase in germane cognitive load to free up mental resources that can process intrinsic cognitive load for storage in long-term memory. Lessons should be designed to present information for the schema students already have and then build off of that schema (van Merriënboer et al., 2002). If intrinsic cognitive load is low, lessons do not normally demonstrate any cognitive load overall (Sweller, Paas & Renkl, 2003). However, if intrinsic load is very high and students do not have existing schema, this problem can be circumvented by presenting worked out problems first (de Jong, 2009).

CAVE impacts on cognitive load. An individual's systems of cognitive processing do not change regardless of what he or she is doing. New technology does not change cognitive processes but can make use of existing cognitive processes if developed with those processes in mind and "can fail abysmally if our burgeoning knowledge of human cognitive architecture is ignored" (Sweller, 2008, p. 32). By understanding components of cognitive load and how it impacts students' abilities to absorb and process new information, educators can be better equipped to design lessons and instructional materials to apply an adequate cognitive load for their students (Chandler & Sweller, 1991; Sweller, 2008). In terms of educational technology, instructional designers may be able to leverage technological tools like VR to alter cognitive load and make it easier for students to process information by enhancing working memory and making questions and concepts more explicit through well designed instructional materials (Lee & Wong, 2014). CAVEs are so novel, even in terms of VR, and require very specific equipment, that it is plausible for CAVEs to have unique impacts on cognitive load by both bolstering spatial ability, similar to other forms of VR (Lee & Wong, 2014), but also by hindering information processing by overwhelming learners with exciting and distracting new technology (Lim & Tay, 2010). Looking more in depth at the CAVE through CLT and instructional strategies will help inform how to use the CAVE to facilitate learning experiences.

There has been a rise in the use of virtual reality as an educational tool as researchers discover the unique affordances it offers in cognitive skills, especially those related to abstract concepts, scientific inquiry and 21st century skills (Merchant et al., 2014; Lee & Wong, 2014). The question is not if CAVEs will affect learners, but how (Dunleavey, 2009), and how it will impact cognitive load to either promote or hinder learning. CAVEs, like other forms of VR, will alter cognitive load (Lee & Wong, 2014), but similar to other educational technology, their potential to augment learning environments must be captured through adequate instructional design (Sweller, 2008). For as many potential positive changes to cognitive load the CAVE could make, inappropriate integration in curriculum or poor lesson design could have counter-productive and negative effects on learning (Sweller, 2008). The following sections describe possible positive and negative effects participating in CAVE lessons could have on the three domains of learners' cognitive loads.

CAVE and intrinsic cognitive load. Intrinsic cognitive load cannot be changed by educators because it is related to the inherent complexity and difficulty of the task or concept (Meissner & Bogner, 2013). However, even the most complex tasks can be subdivided into units that are easier to understand (Ayres & Paas, 2012). Educators can focus students' attention on certain components at a time, turning complex concepts into feasible units by using VR to amplify and simplify content (Finkelstein et al., 2005). Amplifying and simplifying concepts by zooming into and highlighting component parts gives educators the ability to utilize VR as ability-as-enhancer, showing more complex interactions, and as ability-as-compensator, focusing on a few details at a time. These affordances of IVR give it the power to convey concepts with inherently higher intrinsic cognitive load than students may be able to comprehend without the technology (Höffler & Leutner, 2011; Lee & Wong, 2014).

Perhaps one of the most important contributions virtual reality can make to learning is its ability to make intangible physical concepts tangible through the technique called reification (Mikropoulos & Natsis, 2011; Winn, 2002). Reification relies on metaphors created by the designer to turn real-world objects into something that can be perceived in a virtual environment (Winn, 2002). If a concept has no perceptible form, the designer has to create a metaphor from real data that can be rendered into a virtual model by the computer, like using a sphere to represent a neutron or arrows to represent the speed and direction of ocean currents (Winn, 2002). The computer cannot distinguish between reified virtual objects and real objects thus allowing students to view and interact with reifications in exactly the same way that they do with real objects (Winn, 2002) and avoiding the need for learning and memorizing symbols for objects (Mikropoulos & Natsis, 2011). Reification is especially necessary when phenomena or objects are too abstract, large, or small to perceive, thus allowing students to experience in computer-simulated virtual learning environments what they cannot experience in the real-world (Mikropoulos & Natsis, 2011; Winn, 2002). Learning in artificial environments that have reified abstract concepts in the manner described above has helped students understand concepts and processes in astronomy, meteorology, oceanography, maintenance of nuclear reactors, subatomic chemistry, and global warming among other content areas (Winn, 2002).

An advantage of using the CAVE over other forms of VR is that immersion within a simulation made of high fidelity images combined with the ability to look at objects from multiple perspectives means students are interacting with true to life models (Dalgarno & Lee, 2010; Mikropoulos & Natsis, 2011). Viewing accurate representations while immersed in multiple perspectives helps decrease the numbers of students forming misconceptions of spatial concepts (Huk, 2006; Limniou et al., 2008). However, the caveat to this affordance is that many datasets that can be displayed in the CAVE contain more visual information than is relevant to a specific lesson, increasing the likelihood of cognitive overload from extraneous data. Educators must carefully choose which parts to amplify and simplify as virtual environments can easily contain too much information and overwhelm the intrinsic cognitive load with a task that seems more difficult than it is.

Additionally, a risk from relying on the process of reification for transmitting complex, abstract concepts is the potential formation of misconceptions by learners. For example, Jackson, Taylor & Winn (1999) used a virtual environment to teach students about the role of carbon cycling in climate change and chose to emphasize a connection between global warming and deforestation. In the reified metaphor for this complex interaction, as more trees were cut down, the amount of carbon in the atmosphere increased, and vice versa. The students took away from the activity the misconception that replanting forests would solve the complicated issue of climate change (Jackson, Taylor & Winn, 1999). Therefore designers must choose and explain metaphors overall as carefully as deciding on what parts of the data to amplify, simplify, or draw connections between (Winn, 2002) because reifying objects inaccurately or in the wrong context can cause an increase in perceived intrinsic cognitive or actual extraneous cognitive load.

CAVE and extraneous cognitive load. Extraneous cognitive load results from instructional design apart from what is essential for learning and can include instructional materials as well as the setup of the physical learning environment (Sweller, 1988). In the case of the CAVE, since the physical learning environment also includes the virtual learning environment, educators have to consider twice as much with regards to what is going to be taught, how it is going to be taught, and how the equipment required to effectively use the virtual learning environment will influence students' extraneous cognitive loads.

When reducing extraneous load caused by the virtual learning environment, it is imperative that educators revisit the reified objects to determine if the content of the simulation or environment is adequate to meet learning objectives. If the reification contains too much, or the wrong type of information, the result can leave the learner processing unnecessary information. This is explained by the redundancy effect, which occurs if a task comprises more information than is necessary for understanding and can cause learners to invest more working memory on the extraneous information (Chandler & Sweller, 1991; Meissner & Bogner, 2013). Another outcome of poor instructional design is the split-attention effect that occurs if learners have to keep in mind different issues simultaneously (Sweller, 2008). Mental integration of information from different sources increases the amount of working memory required to process it (Chandler & Sweller, 1991; Meissner & Bogner, 2013). When considering instructional design, split-attention effects are reduced if information is given in a condensed rather than a separated form (Chandler & Sweller, 1991). From a CAVE educator standpoint, split-attention and redundancy effects are particularly relevant when considering the 3D environments, simulations, and accompanying instructional materials as they direct educators to make reified phenomena succinct without oversimplifying.

Educators must also consider how the physical environment of the CAVE will impact students from when they walk into the space initially, perhaps exciting their senses with a novel environment, to when they put on a pair of 3D glasses to use the CAVE. In one study, the novelty of the 3D environment was distracting from the educational aspects of the lesson (Lim & Tay, 2010), but carefully designed lessons can focus student attention (Finkelstein et al., 2005).

Beyond the novelty effect, the physical and psychological comfort of 3D glasses, in particular, may increase extraneous load. The 3D glasses work by synchronizing projected images (Baños et al., 2008), and if this feature is not working for some reason, the result can cause the students to either miss the picture because they could not see in 3D or be distracted by the dysfunctional glasses causing them to lose focus on the images (Bamford, 2011).

VR can also have significant physical impacts on users (Bamford, 2011) that could potentially impose extraneous load to the detriment of cognitive load. Bamford (2011) noted 28% of students reported discomfort from headaches, nausea, dizziness, sore eyes, or other eye pain on the first experience wearing 3D glasses during instruction. However, that figure fell to 22.7% on the second viewing of 3D in the classroom, 13.6% on the third viewing and below 4% on subsequent viewings (Bamford, 2011). Only half of the students reported that the glasses used in this study were "good" or "very good" and the major problem was that the glasses were too big and heavy for some of the younger and smaller students. The glasses were the only major problem with the pilot study of 3D in the classroom since many students would take their glasses off or distractedly play with them during the lesson, keeping them from focusing on the content (Bamford, 2011). Poor fitting glasses are a simple and crucial element and can lead to distracted students who may not notice that they are not seeing things correctly in 3D, thus increasing extraneous cognitive load and decreasing germane cognitive load as a result of the physical instructional design.

CAVE and germane cognitive load. Germane cognitive load relates to the cognitive or working memory resources used by learners to problem solve or process information (Sweller, 1988). Researchers have made recommendations for how to help students increase access and use of their working memories, but in the end, the individual is the one who decides if he or she will expend working memory for learning, and if a learner is excited, he or she will choose to devote more working memory to the problem (van Merriënboer et al., 2006). Learners need adequate stimulation in order to expend working memory capacity for learning processes (Schnotz & Kürschner, 2007).

In general, 21st century students seem highly motivated by technology (Gu, Zhu, & Guo, 2013) and use of technology in classrooms appeals to an already apparent interest. In some studies 90% of students have seen 3D movies and a high percentage also played video games regularly so they are already familiar with using and viewing 3D, virtual technology (Bamford, 2011). Because students regularly interact with the technology already, they may be more comfortable and competent with it in the classroom because of existing schema for processing and interpreting images in 3D. Instructional designers have long been attempting to co-opt such technology to increase active participation and learning within classrooms (Dickey, 2005).

Instructional designers who have researched game design notice similar behaviors between gamers and engaged learners in that they are highly active and motivated, (Dickey, 2005). The act of immersing a learner in an educational virtual environment activates the same feeling of presence and engagement as in video games, and an engaged learner will be more motivated to use more cognitive resources from the working memory to create the systems or schema for storing and organizing knowledge related to that virtual environment (Meissner & Bogner, 2013). Additionally, tasks of high variability and appropriate level of teacher guided and student driven opportunities are seen to be advantageous (Bamford, 2011; van Merriënboer et al., 2006) because learners become familiar with other situations in which specific methods of problem solving can be successfully applied (Sweller, 2008).

Table 1

Summary of Cognitive Load Domains and corresponding impacts of CAVE IVR.

Intrinsic Cognitive Load	**Extraneous Cognitive Load**	**Germane Cognitive Load**
Cannot be changed by VR because it is inherent to the difficulty of the task. CAVEs can help change perceived cognitive load by allowing instructors to magnify specific content and subdivide it into more manageable components. CAVEs work best at relaying spatial, 3D content, especially that which is hard for the naked eye to see, and may not function as well for delivering non-spatial content.	CAVEs can increase extraneous cognitive load if the simulations or environment are inadequate for their intended purpose. Often CAVEs display too much information and teachers must work harder to refocus distracted students' attention to relevant information. Physical environment including space and equipment can be over-stimulating and distracting.	Cognitive processing is enhanced by student engagement and motivation. 21st century students are comfortable with technology and find it stimulating, implying the novelty of CAVEs as an exciting educational technology can increase student participation.

Practical Framework: Virtual Reality and Instructional Design

Advanced technology does not automatically improve learning (Winn, 2002), but it does change the way educators teach (Keengwe & Onchwari, 2011; Winn, 2002). The real challenge is not in how to use new technology but in how to change instructional design as a result of how technology affects pedagogy (Finkelstein et al., 2005). Educators need to explore appropriate and innovative ways to make technology useful (Lau & Lee, 2012) because the learning design is what captures the potential of the technology by harnessing its affordances (Dalgarno & Lee, 2010; Mikropoulos & Natsis, 2011). This section discusses current educational pedagogy and practices that could be applied to any future educational uses for the CAVE.

Instructional pedagogy: Constructivism. Constructivism is an educational philosophy that asserts learners construct their own reality, meaning, and knowledge from experiences within real-world contexts (Vygotsky, 1978), and is frequently used as a framework for instructional design for technology (Mikropoulos & Natsis, 2011). In general, the more constructivist a teacher's beliefs, the more likely he or she is to use technology in the classroom because technology is a tool to support thinking in meaningful ways (Keengwe & Onchwari, 2011). Mikropoulos & Natsis (2011) note that a majority of educational virtual environments are actually based on the theory of constructivism and similarly, instructional design that utilizes VR as an educational tool adheres readily to a number of principles of constructivism as outlined below.

Principle 1: Provide multiple representations of reality, not simplifying the natural complexity of the world. Some phenomena in the natural world are just impossible to see without the aid of interpretation. Reification is a method for visualizing the most minute or infinitely large concepts studied in STEM classes. Representation of concepts through reified images does not necessarily simplify the complexity of the natural world, but they are crucial for understanding it. Computer-simulated virtual learning environments allow students to experience what they cannot in the real-world without sacrificing any real-world characteristics (Mikropoulos & Natsis, 2011; Winn, 2002).

Principle 2: Focus on knowledge construction, not reproduction by enabling context, and content, dependent knowledge construction. The role of the teacher using IVR is less as a lecturer, or dispenser of knowledge, and more as a guide, or someone who empowers students to control their own learning in the environment (Keengwe & Onchwari, 2011). In a CAVE, users literally drive their own experiential learning by being given control of the environment (E. Whiting, personal communication, January 26, 2015). Almost all educational virtual environments promote first-person exploration indicating educational researchers understand the differences in affordances offered by VR as compared to other 3D graphic environments (Mikropoulos & Natsis, 2011). Furthermore, heightened presence in IVR could stimulate higher engagement (Bailenson et al., 2008; Dickey, 2005), and facilitate learners' construction of their own understanding from a first-person narrative, rather than as a third-person observer of text or images (Hew & Cheung, 2010). VR has the capacity to enhance learning experiences by providing students with highly heuristic, interactive environments that allow them to learn for themselves (Lau & Lee, 2012).

Principle 3: Present authentic tasks and provide real-world, case-based learning environments. The power of presence is noted as early as the 1970's in the seminal work in social science known as Zimbardo's Prison. In this study civilians were immersed in a physical replication of a prison and observed for the psychological effects on a person becoming either a prisoner or a prison guard. The overwhelming impact of the study on participants is indicative of the ability of constructed environments to evoke authentic behavior and emotional response (Blascovich & Bailenson, 2005). Blascovich and Bailenson (2005) compare concrete physical environments to simulated virtual environments and argue strongly that virtual environments can also provide authentic, real-world experiences. Arguably, the CAVE is able to provide real-world, authentic experiences because when immersed, users react to their environment and the environment responds (Blascovich & Bailenson, 2005). The sense of presence from IVR meets the need for educational environments where the students behave like they do in the real-world (Mikropoulos & Natsis, 2011).

Principle 4: Foster reflective practice. Interacting with models in virtual environments helps bridge the gap between what students have learned, how it might be visually represented (Dickey, 2005), and how it compares to their own mental models (Mikropoulos & Natsis, 2011). This implies that participation in an educational virtual environment requires students to practice reflective thinking. Additionally, students learning in 3D have been observed to ask more and higher quality questions than their counterparts receiving 2D instruction, indicating that they do practice reflection and higher level thinking (Bamford, 2011).

Principle 5: Support collaborative construction of knowledge, not competition. Findings show that collaboration and social negotiation exist while inside and outside the virtual environment (Mikropoulos & Natsis, 2011), as is evident in curriculum using 3D visualization in which participants discussed and collaborated more with peers than students in the control group who were learning in 2D (Bamford, 2011). Additionally, the affordance of CAVEs that allow users to view the same data from multiple perspectives could, by design, help foster higher level discussion.

Instructional practices: Multimedia design principles. One way to understand instruction is as the preparation and arrangement of activities, conditions, and materials that support learners' mental processing in achieving specific learning goals (Gibbs, 2012). Theories of instruction attempt to relate instructional events to learning processes while drawing upon prior knowledge (Gibbs, 2012). Multimedia design principles make recommendations for instructional design using multimedia technology in a way that combines constructivism with CLT and such that they can be applied to the CAVE. The principles of the cognitive theory of multimedia learning draw from CLT and describe a dual-channel theory of processing that proposes brains process information visually or verbally (Mayer, 2002). According to this theory, "appropriate verbal and visuospatial thinking leads to meaningful learning" (Robinson, 2004, p. 10). Mayer (2002) describes visuospatial thinking as the process of constructing knowledge by selecting, organizing, and integrating images while verbal thinking is the process of selecting, organizing, and integrating words.

The CAVE relies heavily on visuospatial processing channels to relay information, but according to the cognitive theory of multimedia learning, comprehension of concepts taught with VR in the CAVE could be enhanced if instructional design stimulated verbal thinking as well (Mayer, 2002; Robinson, 2004). The theory makes recommendations for eight design principles that promote deeper learning with multimedia. The primary idea, the Multimedia Principle, hypothesizes that deeper learning occurs from words and pictures together rather than from words alone. However, the Contiguity Principle posits that words and pictures should be presented at the same time rather than one after another to promote deeper learning. Additionally, the third principle, Modality, suggests that deeper learning occurs when words are presented as narration rather than as on-screen text, but the Redundancy Principle adds that words presented as narration alone rather than as narration with on-screen text will further enhance learning. The fifth principle, Personalization, reminds instructors that when narration and words are presented in a conversational rather than formal style, deeper learning is promoted (Mayer, 2002; Robinson, 2004).

Coherence is the sixth principle that states deeper learning happens when unnecessary or extraneous words, sounds, or pictures are excluded rather than included. The seventh principle, Interactivity, promotes first-hand knowledge construction by theorizing that deeper learning occurs when learners are allowed to control the presentation rate than when they are not. Lastly, the eighth principle, Signaling, states that deeper learning occurs when key steps in the narration are signaled rather than non-signaled (Mayer, 2002; Robinson, 2004). Signaling can also be referred to as cueing and is used to direct learners' attention to specific parts of animations (Ayres & Paas, 2012).

A model for teaching with the CAVE following these multimedia instructional principles would include: 1) Planning to include both teacher and student driven portions of the lesson, to address the Interactivity Principle; 2) Narrating simulations with age-appropriate language while the students are inside the CAVE as opposed to providing a handout which would require them to read information on the handout while simultaneously processing visual information projected in the CAVE. This would address the Modality and Personalization Principles; 3) Verbal cues as text within the virtual simulation next to corresponding images and without narration to address the Contiguity and Redundancy Principles; and 4) Directing students' attention using cues or signals either verbally or visually to highlight important areas of simulations or virtual environments, thus utilizing the Signaling Principle.

Chapter 3

Application of Research to Practice

Educational Technology, CAVE IVR, and Instructional Strategies

The CAVE as an educational technology has incredible potential to alter cognitive load in a way that promotes learning (Lee & Wong, 2014), but like other educational technology if it is insufficiently integrated into the curriculum, it can risk increasing extraneous and germane cognitive loads at the detriment of students' abilities to process or problem solve tasks with higher intrinsic load (Sweller, 2008). Researchers and practitioners teaching with 3D in classrooms have noticed that its use causes changes in pedagogy (Bamford, 2011; Keengwe & Onchwari, 2011). The application of this research, discussed below, should make sure the pedagogical and practical changes necessitated by CAVE IVR are effective and do not overwhelm students' cognitive load but in fact utilize the technology to its fullest benefit. While "there are no EVEs [educational virtual environments] that exploit all the unique features of VR" (Mikropoulos & Natsis, 2011, p. 774), employing the right pedagogical approach and appropriate instructional strategies for teaching with technology will increase the likelihood of successful programs using the CAVE.

In addition to complying with principles of constructivism and the cognitive theory of multimedia learning, lessons relying on CAVE technology need to incorporate the four critical elements of VR including virtual world/space, immersion, sensory feedback, and interactivity (Lau & Lee, 2012), but should also strive to encapsulate the two primary affordances of IVR, sense of presence and multiple perspectives (Mikropoulos & Natsis, 2011). Understanding that effective teaching with technology requires teachers to be aware of the interplay between technology, pedagogy, and content (Lim & Tay, 2010; Keengwe & Onchwari, 2011), this section puts forth a list of instructional guidelines for the CAVE that highlights these areas as they have emerged from the literature.

Lesson design is a multifaceted component of instructional design but it is the key to harnessing the potential of the affordances of any educational technology (Dalgarno & Lee, 2010; Keengwe & Onchwari, 2011). While there are a number of components to instructional design, these six areas stood out in the literature and also in informal observations from experiences of using the CAVE to teach K-12 students. This list is an application of CLT, constructivism, and the cognitive theory of multimedia learning to the CAVE to make recommendations for how to teach with IVR. These guidelines are meant to help instructors utilize the technology to facilitate learning and enhance outcomes rather than detract from lessons with distracting environments or poorly managed instructional resources. The description of each instructional design strategy is followed by suggestions for how to be intentional with design for the CAVE to maximize the use of affordances of the technology in a way that improves cognitive load for learning. Table 2 summarizes this discussion on research into instructional design strategies for IVR in the CAVE and includes suggestions for how to check for alignment with best practices.

IVR Design Strategy 1: Content

Part of designing lessons for cognitive load requires selecting concepts with an adequate intrinsic load for the students and choosing the correct tools for helping students process the cognitive load. Educational researchers have discovered virtual reality is best suited for delivering specific content (3D spatial concepts that are hard to visualize in the physical world) to certain types of students (low spatial ability students) (Höffler & Leutner, 2011; Mayer, 1997; Mikropoulos & Natsis, 2011; Windschitl & Winn, 2000; Winn, 2002). Therefore in order to create a situation with conditions optimal for learning, instructional designers should choose content that has an intrinsic cognitive load that requires spatial visualization skills for processing, especially if the content is impossible to see in the real-world, like many of the concepts taught in STEM classes (Lau & Lee, 2012; Winn, 2002). Because CAVEs are so well suited for teaching 3D spatial content, teaching the wrong content with this tool could unnecessarily increase the perceived cognitive load of a simple task.

As discussed previously, CAVEs are unique in terms of VR because they are immersive and give users a sensation of presence. However, according to Bowman et al. (2007), immersion is not always necessary. Educational technology should support the curriculum not replace it (Bamford, 2011; Hew & Cheung, 2010; Keengwe & Onchwari, 2011), so instructional designers should consider whether or not the lesson could be carried out equally well or better in a physical environment (Hew & Cheung, 2010). If the answer to this question is yes, teaching that lesson in the CAVE might not be appropriate because doing so would be replacing a teaching opportunity in the physical world that may be equally rich as that in IVR. In order to avoid this conflict, an instructional designer should choose content for which immersion and the ability to assume multiple, immersed perspectives would add to understanding and retention.

If the lesson could be taught equally well or better in the real-world, educators should consider changing the objectives of the lesson slightly so that the content could still be covered, but the essential question for the lesson would make it better suited for teaching in the CAVE. An example of rewording an essential question for a high school class relating to understanding the Ideal Gas Law is changing, “What happens to gas molecules in a container as the space inside the container is compressed?” to “What does it look and feel like to be a gas molecule in different parts of a container full of gas molecules as the container is slowly compressed?” A student with naturally high spatial ability might easily be able to answer to the first question using a simple series of illustrations or an animated graphic. However, the second question is asked in a way that still meets the same learning objective but might also enhance learning for low spatial ability students by emphasizing and utilizing the affordances of immersion, sense of presence, and multiple perspectives. Evidence suggests that students immersed in content are more motivated and have a better overall learning experience (Limniou et al., 2008), so asking essential questions that involve changes in perspective may better utilize the affordances of immersion in the CAVE and improve rather than replace learning opportunities with IVR.

IVR Design Strategy 2: Engaging and Interactive

Interactivity is one of the core principles of the cognitive theory of multimedia learning (Robinson, 2004). Lessons that are fun and exciting for students promote active engagement of learners (Mikropoulos & Natsis, 2011), which in turn increases germane cognitive load and students' ability and motivation to solve problems (Dickey, 2005; Meissner & Bogner, 2013). The novelty effect of a new learning environment is often enough to engage students (Lim & Tay, 2010). Additionally, by default, CAVE activities are more interactive than those in other types of VR delivery programs because users physically walk into a virtual environment and can respond to their surroundings via haptic controls (Blascovich & Bailenson, 2005). Nevertheless, instructional design for the CAVE should avoid using virtual environments where users are passively watching simulations like a 3D movie (Bamford, 2011). One design solution that gets students engaged and interacting with the material is to let them actively use the technology to teach their peers (Bamford, 2011; E. Whiting, personal communication, January 26, 2015). Learners may be able to increase their germane cognitive loads if given control over the interactivity of elements in their learning environment (Lee & Wong, 2014).

Another solution to stimulate active participation is to encourage the principles of constructivism – collaboration and communication – because an opportunity for receiving feedback enhances students' learning (Dickey, 2005). Educational virtual environments are well positioned to support constructivist pedagogy and are effective as teaching tools when used in that manner (Mikropoulos & Natsis, 2011). The affordances of immersion and multiple perspectives in the CAVE will naturally be able to increase the richness of discussion as students have the ability to discuss concepts from different viewpoints (Blascovich and Bailenson, 2005).

IVR Design Strategy 3: Differentiation by Ability

In the arena of instructional design, differentiation according to learner needs is an important strategy for being able to work with students of varying abilities and skill levels. Educators who successfully differentiated lessons using VR often relied on the technique of scaffolding, which refers to building lessons from simple to complex by starting with worked examples and increasing over time and with growing expertise to more open-ended problems (Ayres & Paas, 2012; van Merriënboer et al., 2002). In terms of cognitive load domains, differentiation is a technique used to supplement germane cognitive load by providing students with tools to help them process information more easily, depending on their existing schema and knowledge bases. Ordering lessons from simple to complex is one way to prevent learners from experiencing the full intrinsic load at the beginning of a lesson (van Merriënboer et al., 2002; van Merriënboer et al., 2006).

The hypothesis behind differentiating lessons in this way is that by providing learners with outside cues from which to borrow knowledge, extraneous cognitive load would be reduced (Mayer, 1997; Sweller, 2005). However, presenting problems haphazardly without outside knowledge to draw from would increase germane cognitive load because students would be randomly trying to solve problems through trial and error. The more students borrow from existing information by being given important information by instructors, the less random testing they have to do and the more they should learn (Sweller, 2005; Sweller, 2008). "Novices should be given appropriate information and shown appropriate sequences rather than left in the discovery mode" (Sweller, 2005, p. 356).

Because VR is an appropriate tool for teaching spatial, 3-dimensional concepts (Windschitl & Winn, 2000) instructional designers using the CAVE should differentiate according to students' spatial abilities. VR has the potential to help improve learning for students with both low and high spatial abilities (Höffler & Leutner, 2011) and differentiation can help enhance VR's function as both ability-as-compensator and ability-as-enhancer. However, there is a risk that poorly scaffolded lessons could negate any positive influence by overwhelming low spatial ability users with extraneous load while also confronting high expertise learners with redundant information (Meissner & Bogner, 2013).

To avoid this, instructional design should utilize the Signaling Principle of the cognitive theory of multimedia learning to help direct students' attention to important content within the CAVE simulation (Robinson, 2004). Images with directional arrows or color fading will help reduce cognitive load because learners do not have to search as long for information in novel situations (Ayres & Paas, 2012). Additionally, the practice of reification should be utilized to improve scaffolding by amplifying relevant content and minimizing extraneous or redundant data (Mayer, 2002). Amplifying, simplifying, and breaking down content allows students to more easily control the speed of their learning and work at levels appropriate to them, thus affecting their perceived intrinsic cognitive load (Finkelstein et al., 2005).

IVR Design Strategy 4: Presentation

For the sake of this discussion, presentation is a broad category that encompasses aspects of lesson delivery extraneous to content including the amount of time spent on the activity, instructional materials, and the facilitation of classroom management during the lesson. "The proper function of instructional design is to be concerned with how written, spoken, and diagrammatic information should be presented" (Sweller, 2005, p. 355). The CAVE is a tool for presenting diagrammatic visuospatial information and should follow convention for other instructional materials in terms of integrating pictorial and verbal information. Instructors should physically integrate the sources of information in virtual environments by placing text directly next to relevant parts of a diagram rather than having learners unnecessarily use working memory resources in an attempt to mentally integrate them. This will substantially reduce extraneous cognitive load because learners will not need to overburden working memory resources (de Jong, 2009).

Additionally, working memory consists of visual and auditory processors and learning is enhanced when both sets of processors are activated (Mayer, 2002). Information should be narrated as well as demonstrated to adhere to the Multimedia Principle of cognitive theory of multimedia learning (Robinson, 2004), followed by an opportunity for students to explore and construct their own first-person experience. In summary, instructors should take students into the CAVE, show them how to navigate, and then hand over controls (E. Whiting, personal communication, January 26, 2015) rather than giving students a sheet of instructions and asking them to figure everything out on their own.

In terms of the length of time of lessons, elementary school students and teachers interviewed by Bamford (2011) about their preferences for delivery of content in 3D believed lessons should be 10-30 minutes long and 3D lessons should be delivered no more than two or three times per week. The interviewees in this study believed that any more time would perhaps put too much stress on mental resources and germane load or begin to push into the uncomfortable zone of exposure to 3D environments leading to eye pain and dizziness. However, this study focused on one age group and results may vary based on cognitive and behavioral development.

Lastly, the CAVE physical environment is unique because users can walk into a space and be fully immersed in a virtual environment. However, the size of the space limits the number of users that can comfortably fit in the CAVE and still experience the greatest feeling of presence (Blascovich & Bailenson, 2005). In practice, the ideal number of users that should be allowed in the CAVE at one time is no more than five (Limniou et al., 2008; E. Whiting, personal communication, January 26, 2015). Image fidelity is important for stimulating the sensation of presence (Dalgarno & Lee, 2010), but can be compromised if there are too many people standing in front of or on top of the projected images. To that end, instructors should include in their lesson design how to facilitate groups of students inside and outside the CAVE.

IVR Design Strategy 5: Physical and Virtual Environments

Learning environments, whether real or simulated are a significant part of instructional design extraneous to the actual task at hand (de Jong, 2009). The novelty of the physical and virtual environments of a CAVE can be over-stimulating and distracting for some students, more so than other forms of VR, thus impeding germane cognitive load and the ability to process new information (Lim & Tay, 2010). Instructors must design lessons using the CAVE to counter the negative novelty effects of IVR and focus attention on content and learning objectives (Finkelstein et al., 2005). Focusing attention can be accomplished by removing redundant or unnecessary information and materials (Meissner & Bogner, 2013; Sweller, 2008) within the physical space and the virtual space. In practice, limiting redundancy in the virtual space can be accomplished by previewing simulations or environments to be prepared to draw students' attention to specific data. In the physical space, this can be done by preparing students with clear descriptions and expectations of the physical CAVE space.

Additionally, instructors must make sure students are in a physical environment that is comfortable. The physical environment of a CAVE is unique in that it requires students to wear sometimes bulky, ill-fitting glasses and then be immersed in a potentially disorienting, unfamiliar virtual environment (Bamford, 2011). Extraneous physical factors can cause students to lose focus on the content, thus also decreasing their germane cognitive processing ability. To minimize distraction from the novelty effect of the CAVE, prepare students by explaining what they can expect in terms of physical and emotional impacts of participating in a virtual environment (Lim & Tay, 2010).

The 3D glasses can be bothersome for some students and if they are, work with the students to alleviate discomfort by adding extra padding or adjusting nose pieces as necessary (Bamford, 2011). Another discomfort that might arise is a feeling of dizziness and nausea from motion sickness within the CAVE. Bamford (2011) noted feelings of dizziness and eye pain were greatest during the first session in 3D and had diminished drastically by the fourth session, so perhaps lesson plans should stretch over multiple days allowing for the greatest learning to happen after users have become accustomed to the environment and equipment. Overall, carefully designing the environments and preparing students for participating in both physical and virtual environments will help reduce extraneous cognitive loads and increase germane cognitive loads.

IVR Design Strategy 6: Technical Knowledge

Many 21st century learners have grown up in a world rich with technology and are often more comfortable and confident with virtual technologies than their teachers, becoming competent with IVR very quickly (Gu et al., 2013). However, teachers still need to be savvy enough to guide students through lessons since the role of the teacher in educating with technology is crucial (Lim & Tay, 2010). Successful teaching using technology requires teachers to have practical experience and a reasonable level of skill in using the technology (Keengwe & Onchwari, 2011). Instructors should be familiar with the technology before using it especially in terms of navigating simulations and virtual environments and being able to move seamlessly through lessons and between instructional strategies in each lesson. In practice, navigating through simulations in the CAVE can be a difficult skill to master and moving too slowly or too quickly can cause users to become disengaged or even develop motion sickness. Being able to move fluidly through simulations could help retain student attention, limit distraction from unnecessary technical difficulties, and model appropriate behavior with the technology.

The CAVE is a unique form of virtual reality delivery, and as with many educational technologies, the initial barriers to adoption lie in large part in teachers' confidence in using the technology (Gu et al., 2013). However, teacher confidence with 3D technology can improve with extended use of technology (Bamford, 2011). Preparation ahead of time to get a good grasp of what parts of the content are explicitly displayed (Hew & Brush, 2007) or collaboration with people who have the appropriate skills will make lessons more effective.

Table 2

Summary of instructional design guidelines for CAVE technology and suggested questions to help check for alignment with best practices.

Instructional Design Strategy	**Cognitive Load Area**	**Instructional design guidelines for CAVE**	**Probing questions to check for alignment with guidelines**
Lesson design: *Content*	Intrinsic	• Best content in CAVEs is 3D (Windschitl & Winn, 2000) and often impossible to see in the real-world (Winn, 2002). • Not everything needs to be taught in 3D; immersion does not necessarily improve learning (Bowman et al., 2007).	• Is content spatial in nature? • Is the content impossible to see in the real-world? • Does the lesson objective require seeing something from an immersed perspective?
Lesson design: *Engaging & Interactive*	Germane	• Engaged learners have more processing ability (Meissner & Bogner, 2013). • Best outcomes in the CAVE are when students are involved (E. Whiting, personal communication, Jan. 26, 2015).	• Are students doing more than passive observation? • Are students allowed to interact with and control virtual environments?
Lesson design: *Differentiation*	Germane & Extraneous	• CAVEs can help low and high spatial ability students, but risk overwhelming low spatial ability students while being too simple for high spatial ability students (Höffler & Leutner, 2011). • Best lessons use scaffolding (van Merriënboer et al., 2002).	• Does the lesson start with worked examples and conclude with open-ended problems? • Are there opportunities to work at different levels or speeds?
Lesson design: *Presentation*	Germane & Extraneous	• Instructional materials can provide unnecessary information (Meissner & Bogner, 2013). • There is an optimal group size in the CAVE at a time (E. Whiting, personal communication, Jan. 26, 2015) and preferred time lengths (Bamford, 2011). • Best lessons integrate visual and verbal information (Mayer, 1997).	• Is CAVE simulation integrated with spoken instructions and other instructional materials? • Is signaling or cueing used? • Will students be managed for groups of 5 in the CAVE? • Is time in the CAVE 30-60 minutes?
Space: *Physical and virtual environments*	Extraneous	• Novelty of virtual environments can impede learning if it is over-stimulating and distracting (Lim & Tay, 2010). • IVR and equipment can be disorienting and cause discomfort (Bamford, 2011). • Repeated uses can reduce negative impact of novel VR experiences (Bamford, 2011).	• Have students received an overview and expectations for the CAVE? • Has the instructor previewed the simulation to be able to direct attention to the content? • Is the session one of many opportunities with the CAVE?
Technology: *Technical knowledge*	Extraneous	• Best results teaching with technology require experience and skill in using it (Keengwe & Onchwari, 2011).	• Can the instructor start, stop, run, and navigate simulations fluidly without support?

Chapter 4

Practical Application of IVR Guidelines

In practice, effective use of educational technology in a well-designed lesson plan "…a) supports the curriculum objectives being assessed, b) provides opportunities for student collaboration and project-based and inquiry-based learning; c) adjusts for students' abilities; d) is integrated throughout the lesson, [and] e) provides opportunities for students to design and implement projects that extend the curriculum content being assessed…" (Keengwe & Onchwari, 2011, p. 242). Despite the many nuances of high quality lesson planning, this research posits that there are a few instructional design strategies that stand out among the rest and are the key to capturing the potential of the affordances of CAVE IVR for education. When applied, these strategies may lead to lessons that support enhanced cognitive load for learners in the CAVE. An example of such a lesson is outlined in Figure 1. Specific areas that correspond to CLT, principles of constructivism, cognitive theory of multimedia learning are italicized in the example lesson plan. Relevant IVR instructional design recommendations as discussed above follow in parentheses.

Lesson title: Ideal gas law in action ($PV=nRT$)

Grade: High school

Standards: NGSS HS PS3.A – Definitions of Energy. *This content is spatial in nature and is nearly impossible to see with the naked eye without reification (IVR Design Strategy 1).*

Figure 1. Example lesson plan for teaching in the CAVE, applying Cognitive Load Theory and principles of constructivism and cognitive theory of multimedia learning, with IVR guidelines (in parentheses).

(Figure continues)

Figure 1 (*continued*)

Essential question:

- What does it look and feel like to be a gas molecule in different parts of a container full of gas molecules as the container is slowly compressed? *This question refers to a 3D concept and is asked in a way that encourages immersion, unique perspectives (IVR Design Strategy 1).*

Preparation:

- Find and select an appropriate simulation that gives students the sensation of changing into a gas molecule and being placed inside a sealed but adjustable container. *This relates to reification and selection of an appropriate metaphor to avoid misconceptions (IVR Design Strategy 1 & 5).*
- Practice starting, stopping, and resetting the simulation from the beginning, as well as using the haptic controller to alter pressure, volume, and temperature settings in the container. *This will help instill the technical knowledge needed to minimize extraneous load from jerky transitions and information overload (IVR Design Strategy 6).*
- Develop a plan for managing students outside the CAVE space with guided worksheets, activities, observations, or other tasks. *This relates to helping minimize distraction and extraneous cognitive load and can also assist scaffolding (IVR Design Strategy 5).*

Introduction:

- Before entering the CAVE, give students an introduction to the space using pictures, videos, or verbal information of the physical and virtual spaces. Include behavioral and academic expectations to help mentally prepare students for the activity and experience. *This will help limit extraneous cognitive load that could result from the novelty effect and increase germane cognitive load by getting students excited for the lesson (IVR Design Strategy 5).*

Lesson Plan Instructions:

- Re-introduce the physical space and equipment, answering any questions about it.
- Re-emphasize behavioral and academic performance expectations and explain lesson learning objectives.

(Figure continues)

Figure 1 *(continued)*

- Explain the potential for motion sickness inside the CAVE and what to do if that occurs. *Building an awareness of potential extraneous load may help alleviate its negative impacts (IVR Design Strategy 5).*
- Separate students into working groups of five or less to take turns rotating through the CAVE. Give instructions for what to do when inside or not inside the CAVE. Stations, worksheets, or experiments related to the essential question would all be appropriate. *This will help students stay focused and continue building or working with relevant schema when outside the CAVE (IVR Design Strategy 4).*
- Enter the CAVE initially with each group of students to give an overview of how to use the equipment to navigate simulations, but then let the students do the driving. *This will utilize the Interactivity multimedia design principle and promote first-hand knowledge creation (IVR Design Strategy 2).*
- Provide each group in the CAVE with a record keeping sheet or other materials with prompts to facilitate working through the CAVE lesson. *This will assist with completing semi-worked examples (IVR Design Strategy 3 & 4).*
- *Scaffold the lesson to meet the needs of students with different spatial abilities (IVR Design Strategy 3).* Begin by having students observe worked examples. Students should be given control and allowed to increase and/or decrease pressure, volume, temperature, or the amount of gas molecules within the container (*IVR Design Strategy 2).* At this time, make sure labels are showing in the CAVE simulation that can indicate feedback as each variable is altered (barometer showing pressure, thermometer showing temperature, scale showing volume, etc.). *Color coding for variables or other visual signals can help students via the Signaling Principle (IVR Design Strategy 4).*
- Students should observe that an increase in pressure and/or volume causes an increase in temperature and an increase in gas molecules causes an increase in pressure and/ or volume. Prompt students to *look from multiple, immersed perspectives (IVR Design Strategy 1)* so that they can identify if the change is uniform throughout the container.
- After students have determined the results of altering variables in the semi-worked examples, *give them an opportunity to free explore, promoting first-hand knowledge construction (IVR Design Strategy 2).*

(Figure continues)

Figure 1 *(continued)*

- *Ask group members to collaborate, a primary principle of constructivism, to hypothesize and answer new questions (IVR Design Strategy 2).* What happens if they alter two variables? What happens if the size of the container is fixed? The end goal for the activity and exploration is for each student to be able to come up with an explanation that describes the relationship between pressure, volume, temperature and the amount of gas molecules in the container – the ideal gas law, $PV = nRT$.
- *Following the idea of scaffolding, evaluate the lesson by giving each group of students a more open-ended scenario (IVR Design Strategy 3).* Each scenario can be different, but none of them should have labels. Instruct the students to play out the scenario, making observations about what happens to gas molecules. The students should write a description of what is happening inside the container along with an explanation of why it happens.
- To extend the lesson, have students hypothesize what would happen with different types of gas molecules or fluid. If possible, allow students to work through the same simulation with different molecules and test their hypotheses. *This will add another level of scaffolding for differentiated instruction with open ended examples that require high levels of expertise and spatial ability (IVR Design Strategy 3).*

Chapter 5

Reflections on Research

Limitations

IVR is still a fairly nascent technology, especially as an educational tool and there still remains a dearth of research on such applications for CAVE technology. Gaps in the literature persist on CAVE technology and its efficacy as an educational tool as well as in how virtual reality in general could affect cognitive load. Researchers in the area of educational technologies have emphasized a need for more studies to explore if and how emerging technologies like IVR can be leveraged for enhanced learning (Dunleavy, 2009). This study begins to theorize how CAVE technology can be used for improving learning by discussing how to use the tool effectively. However, limitations to this study result from a lack of peer-reviewed and scholarly research available on CAVE technology as well as on how virtual reality in general can impact cognitive load. Additionally, a short research timeframe left little time for thorough investigation of the literature or testing and evaluating any proposed CAVE instructional design strategies.

Future Studies

The gap in literature indicates that CAVE IVR has innumerable possibilities for future studies, including in the field of education. Research exists on the impacts of 3D simulations on cognitive load (Lee & Wong, 2014), but not specifically for virtual reality or immersive virtual reality. However, the CAVE is only one type of IVR system and there may be other types of IVR that are better suited for teaching spatial concepts to large groups of students at a time. This research should be expanded to include analysis of other IVR delivery systems such as the

Oculus Rift, a head-mounted technology that is becoming increasingly available on the consumer market.

In general, the educational research area with greatest need for future studies in VR and IVR is in more reliable assessment of how the technology affects students. The literature is full of data collected from short term studies with the results largely self-reported by students. There is great need for longer term studies with more accurate methods for assessing student learning and retention over time after participating in 3D VR lessons.

Additionally, there is a need for more information on how IVR affects cognitive loads of students, especially how it affects students of different ages and behavioral maturity levels. The majority of research conducted has been with high school and undergraduate level students, leaving room for research with other ages and abilities of learners. Perhaps the proposed best practice guidelines apply more to certain groups of learners over others, and a better understanding of cognitive load at different developmental levels would greatly influence the future of the CAVE as an educational technology. The result may be that IVR is simply not appropriate as an educational tool for some students due to lack of behavioral, emotional, or cognitive maturity.

Specific to this research, assessment could be done on each of the criteria for CAVE instructional design best practices outlined above. It is possible that one of the design areas is more important than another, one is irrelevant or needs revision, or perhaps there is an important unknown that has not yet been listed. To evaluate, these practices can be applied to lessons and analyzed for their relevance, efficacy in planning and lesson delivery, and importance relative to each other.

Additional future studies are in the area of professional development for teachers to improve the quality of programs delivered in the CAVE. Teachers should be trained on how to appropriately use the CAVE and other virtual reality educational tools to design and deliver content using these guidelines. This would also address the need for developing teachers' confidence with technology.

Conclusion

Having taught students in of a wide range of ages and maturity levels in the CAVE, it is clear that the CAVE has unmet potential as an educational tool. The near instantaneous excitement of students upon entering the CAVE demonstrates that it has the ability to engage students to actively participate, with the caveat that students may be too excited to stay focused on any educational task. Those observations highlight the, as of yet, poorly investigated effects CAVE technology may have on learners' cognitive loads. This research is simply a start for understanding the affordances of the CAVE and how they could impact the three domains of cognitive load, thus helping illuminate how IVR like the CAVE can add to or detract from learning. As new educational technology like IVR becomes available, existing instructional design for technology will need to be amended accordingly. The goal of this research was to determine how to update instructional design strategies for educational technology and fill the gap surrounding pedagogy and practice with immersive virtual technology.

Considering CAVEs' potential as an educational tool and how it could positively and negatively impact student cognitive load has informed recommendations on how to design instructional materials and lessons using the CAVE to enhance cognitive load and improve learning. The recommendations are in the areas of content, differentiated instruction, interactivity of instruction, presentation of learning materials, virtual and physical spaces, and technical knowledge. To summarize, content should be spatial in nature, lessons should engage students by allowing them to navigate virtual environments first-hand, instructional materials should not be redundant but should effectively integrate verbal and visual information, instructors should have a plan on how to facilitate groups of students in the CAVE and outside of it, students should be provided with what to expect from the physical and virtual spaces to minimize the novelty effect, and instructors should have some practice with the technology before teaching with it. While there still remains a great deal to understand about the potential of IVR for education, these up to date instructional guidelines for this emerging technology will help ensure the affordances of the CAVE are being utilized in a way that enhances learning opportunities for students rather than overwhelming their germane cognitive loads or over-stimulating them with unnecessary information.

References

Ayres, P., & Paas, F. (2012). Cognitive load theory: New directions and challenges. *Applied Cognitive Psychology, 26*(6), 827-832. doi:10.1002/acp.2882

Bailenson, J., Yee, N., Blascovich, J., Beall, A., Lundblad, N., & Jin, M. (2008). The use of immersive virtual reality in the learning sciences: Digital transformations of teachers, students, and social context. *Journal of the Learning Sciences, 17*(1), 102-141. doi:10.1080/10508400701793141

Bamford, A. (2011). Evaluation of innovation in learning using emerging technologies. Report for *LiFE: Learning in Future Education.* London, UK.

Baños, R. M., Botella, C., Rubió, I., Quero, S., García-Palacios, A., & Alcañiz, M. (2008). Presence and emotions in virtual environments: The influence of stereoscopy. Cyberpsychology and Behavior, 11(1), 1-8. doi:10.1089/cpb.2007.9936

Blascovich, J. and Bailenson, J. (2005). Immersive virtual environments and education simulations. In S. Cohen, K.E. Portney, D. Rehberger & C. Thorsen (Eds.), *Virtual decisions: Digital simulations for teaching reasoning in social science and humanities immersive virtual environments (*229-253). Mahwah, NJ: Lawrence Erlbaum Associates.

Chandler, P., & Sweller, J. (1991). Cognitive load theory and the format of instruction. *Cognition and Instruction, 8*(4), 293-332. doi:10.1207/s1532690xci0804_2

Chen, C., Jen, Toh, S., Chong, & Fauzy, W., Mohd. (2004). The theoretical framework for designing desktop virtual reality-based learning environments. Journal of Interactive Learning Research, 15(2), 147.

Crosier, J. K., Cobb, S., & Wilson, J. R. (2002). Key lessons for the design and integration of virtual environments in secondary science. *Computers & Education, 38*(1), 77-94. doi:10.1016/S0360-1315(01)00075-6

Dalgarno, B., & Lee, M. J. W. (2010). What are the learning affordances of 3-D virtual environments? *British Journal of Educational Technology, 41*(1), 10-32. doi:10.1111/j.1467-8535.2009.01038.x

Dede, C. (2009). Immersive interfaces for engagement and learning. Science, 323(5910), 66-69. doi:10.1126/science.1167311 de Jong, T. (2010). Cognitive load theory, educational research, and instructional design: Some food for thought. Instructional Science, 38(2), 105-134. doi:10.1007/s11251-009-9110-0

Dickey, M. D. (2005). Engaging by design: How engagement strategies in popular computer and video games can inform instructional design. *Educational Technology Research and Development, 53*(2), 67-83.

Dunleavy, M., Dede, C., & Mitchell, R. (2009). Affordances and limitations of immersive participatory augmented reality simulations for teaching and learning. Journal of Science Education and Technology, 18(1), 7-22. doi:10.1007/s10956-008-9119-1

Finkelstein, N. D., Adams, W. K., Keller, C. J., Kohl, P. B., Perkins, K. K., Podolefsky, N. S., & Reid, S. (2005). When learning about the real world is better done virtually: A study of substituting computer simulations for laboratory equipment. *Physical Review Special Topics - Physics Education Research, 1*(1) doi:10.1103/PhysRevSTPER.1.010103

Gibbs, W.J. (2012). New media and digital learners: An examination of teaching and learning. In Sharmila Pixy Ferris (Eds.), *Teaching, learning, and the net generation: Concepts and tools for reaching digital learners* (289-309). Hershey, PA: IGI Global.

Gu, X., Zhu, Y., & Guo, X. (2013). Meeting the "digital natives": Understanding the acceptance of technology in classrooms. *Journal of Educational Technology & Society, 16*(1), 392-n/a.

Hew, K. F., & Brush, T. (2007). Integrating technology into K-12 teaching and learning: Current knowledge gaps and recommendations for future research. *Educational Technology Research and Development, 55*(3), 223-252.

Hew, K. F., & Cheung, W. S. (2010). Use of three-dimensional (3-D) immersive virtual worlds in K-12 and higher education settings: A review of the research. *British Journal of Educational Technology, 41*(1), 33-55. doi:10.1111/j.1467-8535.2008.00900.x

Hinze, S. R., Williamson, V. M., Shultz, M. J., Williamson, K. C., Deslongchamps, G., & Rapp, D. N. (2013). When do spatial abilities support student comprehension of STEM visualizations? *Cognitive Processing, 14*(2), 129-142. doi:10.1007/s10339-013-0539-3

Höffler, T. N., & Leutner, D. (2011). The role of spatial ability in learning from instructional animations – evidence for an ability-as-compensator hypothesis. *Computers in Human Behavior, 27*(1), 209-216. doi:10.1016/j.chb.2010.07.042

Huk, T. (2006). Who benefits from learning with 3D models? the case of spatial ability. *Journal of Computer Assisted Learning, 22*(6), 392-404. doi:10.1111/j.1365-2729.2006.00180.x

Jackson, R., Taylor, W., and Winn, W. D. (1999). Peer collaboration in virtual environments: An investigation of multi-participant virtual reality applied in primary science education. Paper presented at the Annual Meeting of the American Educational Research Association, Montreal, Canada, April 1999.

Keengwe, J., and Onchwari, G. (2011). Fostering meaningful student learning through constructivist pedagogy and technology integration. In Laurence A. Tomei Editor (Eds.), *Learning tools and teaching approaches through ICT advancements* (239-249). Hershey, PA: IGI Global.

Ketelhut, D. J., & Nelson, B. (2010). Designing for real-world scientific inquiry in virtual environments. *Educational Research, 52*(2), 151-167. doi:10.1080/00131881.2010.482741

Lau, K. W., & Lee, P. Y. (2012). The use of virtual reality for creating unusual environmental stimulation to motivate students to explore creative ideas. *Interactive Learning Environments,* , 1-16. doi:10.1080/10494820.2012.745426

Lee, E. A., & Wong, K. W. (2014). Learning with desktop virtual reality: Low spatial ability learners are more positively affected. *Computers & Education, 79*, 49-58. doi:10.1016/j.compedu.2014.07.010

Lim, C., & Tay, L. (2010). An activity theoretical perspective towards the design of an ICT-enhanced after-school programme for academically at-risk students. *Educational Media International, 47*(1), 19-37. doi:10.1080/09523981003654951

Limniou, M., Roberts, D., & Papadopoulos, N. (2008). Full immersive virtual environment CAVE in chemistry education. *Computers & Education [H.W. Wilson - EDUC], 51*(2), 584.

Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions? Educational Psychologist, 32(1), 1-19. doi:10.1207/s15326985ep3201_1

Mayer, R. E. (2002). Cognitive theory and the design of multimedia instruction: An example of the Two-Way street between cognition and instruction. New Directions for Teaching and Learning, 2002(89), 55-71. doi:10.1002/tl.47

Mechdyne Corporation. (2012). *Enter the CAVE.* Retrieved from http://www.mechdyne.com/filesimages/Hardware/CAVE/Cave%20Diagram%202012.pdf

Meissner, B., & Bogner, F. (2013). Towards cognitive load theory as guideline for instructional design in science education. *World Journal of Education, 3*(2), 24-n/a.

Merchant, Z., Goetz, E. T., Cifuentes, L., Keeney-Kennicutt, W., & Davis, T. J. (2014). Effectiveness of virtual reality-based instruction on students' learning outcomes in K-12 and higher education: A meta-analysis. Computers & Education, 70, 29-40. doi:10.1016/j.compedu.2013.07.033

Mikropoulos, T. A., & Natsis, A. (2011). Educational virtual environments: A ten-year review of empirical research (1999–2009). *Computers & Education, 56*(3), 769-780. doi:10.1016/j.compedu.2010.10.020

Next generation science standards: For states, by states (2013). National Academies Press.

Pivec, M. (2007). Editorial: Play and learn: Potentials of game-based learning. *British Journal of Educational Technology, 38*(3), 387-393. doi:10.1111/j.1467-8535.2007.00722.x

Schifter, C. C., Ketelhut, D. J., & Nelson, B. C. (2012). Presence and middle school students' participation in a virtual game environment to assess science inquiry. Journal of Educational Technology & Society, 15(1), 53.

Schnotz, W., & Kürschner, C. (2007). A reconsideration of cognitive load theory. Educational Psychology Review, 19, 469-508. http://dx.doi.org/10.1007/s10648-007-9053-4

Sweller, J. (1988). Cognitive load during problem solving: Effects on learning. *Cognitive Science, 12*(2), 257-285. doi:10.1016/0364-0213(88)90023-7

Sweller, J. (2005). Discussion of 'Emerging topics in cognitive load research using learner and information characteristics in the design of powerful learning environments.' *Applied Cognitive Psychology. 20*, 353-357. doi: 10.1002/acp.1251

Sweller, J. (2008). Cognitive load theory and the use of educational technology. *Educational Technology, 48*(1), 32-36.

Sweller, J., Paas, F., & Renkl, A. (2003). Cognitive load theory and instructional design: Recent developments. Educational Psychologist, 38(1), 1-4. doi:10.1207/S15326985EP3801_1

Van Merriënboer, J., Kester, L., & Paas, F. (2006). Teaching complex rather than simple tasks:

Balancing intrinsic and germane load to enhance transfer of learning. *Applied Cognitive Psychology, 20*(3), 343-352. doi:10.1002/acp.1250

Van Merriënboer, J., Schuurman, J., De Croock, M., & Paas, F. (2002). Redirecting learners' attention during training: effects on cognitive load, transfer test performance and training efficiency. Learning and Instruction, 12, 11-37. http://dx.doi.org/10.1016/S0959-4752(01)00020-2

Vygotsky, L. (1978). *Mind in Society.* London: Harvard University Press.

Windschitl, M. & Winn, B. (2000). A virtual environment designed to help students understand science. *Fourth International Conference of the Learning Sciences.* In B.J. Fishman & S.F. O'Connel-Divelbiss (Eds.), Paper presented at the International Conference of the Learning Sciences in Ann Arbor, MI, June 14-17. (290-296).

Winn, W. (2002). Research into practice: Current trends in educational technology research: The study of learning environments. *Educational Psychology Review, 14*(3), 331-351. doi:1016068530070

Author's Biography

Leah T. Ritz attended Macalester College in Minnesota where she earned Bachelors of Arts degrees in Environmental Studies and Geography. She served two terms in AmeriCorps in the Twin Cities where she developed a passion for informal STEM education. Her new found interest led her to continue working at a variety of out-of-school time STEM-related programs ranging from urban gardening to electrical engineering. She attended the graduate program at Teton Science Schools in Wyoming where she practiced place-based education and field ecology. Her studies have taken her to the University of Wyoming where she received a Master's in Science in Natural Science Education and Environment and Natural Resources, and she hopes to continue following her passion for informal STEM education.