ABSTRACT

HITE, REBECCA LYN. Perceptions of Virtual Presence in 3-D, Haptic-Enabled, Virtual Reality Science Instruction. (Under the direction of M. Gail Jones).

Virtual presence describes the degree of immersion and control a user perceives while immersed in a virtual environment. This dissertation work examined the relationships between cognitive development and adolescents perceptions' of virtual presence using 3-D, haptic-enabled (HE) virtual reality (VR) science instruction.

Presence is the psychological perception of being (involved and immersed) in a virtual environment despite being physically situated in reality. Four factors comprise presence: control, sensory engagement, distraction, and realism. A mixed-methods design was used to examine virtual presence, cognitive development and learning gains with seventy-five 6th and seventy-six 9th grade students who participated in a learning module about cardiac anatomy and physiology using a 3-D, HE VR technology system. Prior to instruction, participants completed a pre-assessment on cardiac anatomy and physiology and an assessment of Piagetian development. Upon completion of the learning experience, a presence survey and post-assessment were completed. Data were analyzed by comparing 6th and 9th grade groups, evaluating pre and post assessment scores, correlating Piagetian subject areas to the four factors comprising presence and levels of student questioning on cardiac form and function. Analyses showed there were significant gains for both groups on tests of cardiac knowledge. Although presence was not significantly different between grade levels, 6th grade students' cognitive development in spatial rotation and angular geometry was positively correlated with perceived control and negatively correlated to distraction. Students' prior knowledge played a considerable role in learning, correlations were found in all five Piagetian task categories and pre-test scores for 9th grade students. Ninth grade students, as compared to 6th grade students, may have had prior academic experiences learning about the heart. Results suggest that cardiac anatomy and physiology may be a more developmentally appropriate and motivating learning activity for 9th grade students. This study offers important insight into the best application of 3-D HE VR technologies for use in the K-12 science classroom.

Perceptions of Virtual Presence in 3-D, Haptic-Enabled, Virtual Reality Science Instruction

by
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DEDICATION

For Rosie Burnham Miller.

BIOGRAPHY

Rebecca Hite earned her bachelors in Biology, Geography and Masters in secondary science education degrees from the University of North Carolina at Chapel Hill. She has taught high school science and geography for 13 years in the public schools of North Carolina. During her tenure teaching, she received her National Board Certification, was awarded a Kenan Fellowship at North Carolina State University, served as American Physiological Society teacher-researcher at the University of North Carolina's McAllister Heart Institute and served as a Congressional Albert Einstein Distinguished Educator Fellow in Washington, D.C.

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CHAPTER 1: Three Dimensional, Haptic-Enabled, Virtual Reality Science Instruction

Introduction and Background

Educational technology is quickly evolving with the use of three-dimensional (3-D), haptic-enabled (HE), virtual reality (VR) systems. The high costs once associated with this technology and substantial computational power required had previously made this equipment prohibitive in mainstream school settings (Dalgarno & Lee, 2010, p.11). Today, these tools have the potential to promote learning of science concepts using realistic graphics and touch technology in a user-friendly interactive and immersive interface. With the use of high quality graphic images, simulated movements and auditory stimuli, these systems have potential to enable students to visualize abstract science concepts like particle relationships (Uchiyama & Funahashi, 2013), construct large-scale complex models (Sampaio, Ferreira, Rosário, & Martins, 2010) and feel objects beyond their reach in the typical science classroom like the beating of a human heart (Jones, Hite, Childers, Corin, Pereyra, Chesnutt, & Goodale, 2015). This marks a significant departure from traditional means of science instruction: supplanting flat 2-D images and detached multi-media content presentations with robust 3-D imagery and responsive teaching.

A hallmark of modern K-12 education reform is to personalize instruction via technology to provide students with authentic representations of science processes and scientific endeavors. In the field of surgical oncology, VR simulators have instrumental in enhancing doctor's technical skills and improving performance in the operating room (Lewis, Aggarwal, Rajaretnam, Grantcharov, & Darzi, 2011). In dance, VR simulation has evidenced its utility in the learning and transfer of complex motor skills to the real world (Eaves, Breslin, van Schaik, Robinson, & Spears, 2011). If adolescent and younger learners perceive these representations as authentic, or equally authentic, to other forms of science instruction, these systems may provide a powerful learning opportunity for students who benefit most from one-on-one instruction coupled with visual scaffolding of complex scientific phenomena (Scutaru, Scapolla, Mustica, Sandu, & Kristaly, 2008). These tools may prove particularly useful for students from historically under-served or under-performing groups in science including English language learners (Chung, 2012; Davis & Berland, 2013; Lin & Lan, 2015) and students with disabilities (Lota, Yalon-Chamovitz, & Weiss, 2011; Ludlow, 2015; Vasquez, Nagendran, Welch, Marino, Hughes, Koch & Delisio, 2015). A better understanding of how students interact with and perceive the authenticity of VEs produced by these devices as instructional guides is paramount as they become available to teachers and incorporated into classroom practice (Hite, Jones, Childers, Chesnutt, Corin, & Pereyra, 2016; Zudilova-Seinstra, Adriaansen, & van Liere, 2009). Elucidating these relationships between learners' cognitive attributes and their perception of presence can inform educators about pedagogical strategies to best leverage 3-D HE VR use in K-12 science instruction.

Statement of the Problem

Three-dimensional virtual environments create the visual illusion of objects having depth and realistic qualities (Wann & Mon-Williams, 1996; Dalgarno & Lee, 2010). In Dalgarno and Lee's (2010) model of learning in 3-D VEs, the quality and authenticity of the display (representational fidelity) coupled with precise user actions (learner interaction) are paramount features of these unique technology-enhanced (TELE) or computer-enhanced (CELE) learning environments. In the context of this paper, technology- or computer-enhanced learning environments are defined as simulated classroom activity to support and facilitate learning within a particular subject or discipline (science) where the technological tool is not the objective of the lesson (Shapiro, Roskos, & Cartwright, 1995). A unique aspect of superior 3-D VR technologies is that they employ high-fidelity, photorealistic images mimicking the behavioral interactions the user would experience in reality. This type of virtual environment conveys a rich and robust experience that is both compelling (Wouters, van Nimwegen, van Oostendorp, & van der Spek, 2013) and engaging to the user (Graesser, D'Mello, & Strain, 2014). In this type of experience, the user characteristically experiences to some degree a psychological phenomenon described as a diminished sense of one’s immediate surroundings (Bulu, 2012) transposed with a sensation of physical transportation to a simulated realm where the virtual experience feels authentic (McCreery, Schrader, Krach, & Boone, 2013). This construct is known as virtual presence (Fowler, 2015).

Dalgarno and Lee (2010) argue that “representational fidelity” and “learner interaction” are the two unique characteristics of 3-D, VEs. Representational fidelity refers to the quality of the display whereas high fidelity regards the production of realistic or photorealistic images (Zeltzer, 1992). Realism not only refers to the visual quality of the display, but also the consistency of an object’s behavior through user communication and actions (Fowler, 2015).

In addition to visual modalities, VEs may also incorporate force generating technologies, called haptics (Jones & Minogue, 2006). Haptic-enabled technologies provide touch-based sensory feedback to the user through a hardware interface (grip, stylus or hologram) that provides various tactile sensations (e.g. force or vibrations) to simulate texture, pressure, resistance, weight, or speed (Jones & Minogue, 2006). This technology has been studied in K-12 classrooms to explore students learning gains studying abstract scientific phenomena such as temperature and pressure (Jones, Childers, Emig, Chevrier, Hong, Stevens, & List, 2014), eukaryotic cell structure (Jones, Andre, Kubasko, Bokinsky, Tretter, Negishi, & Superfine, 2004), and lever systems (Wiebe, Minogue, Jones, Cowley, & Krebs, 2009). Since presence (defined below) is a psychological product of multiple sensory inputs (Witmer & Singer, 1994), touch technology may play an important and promising role in inducing or sustaining presence in VEs.

A key component of learning in VEs is invoking a user's sense of virtual presence, where representational fidelity and learner interaction foster a unique psychological experience of being within a virtual realm (Zeltzer, 1992). Presence occurs when a person is unable to differentiate the sensory information from a hardware-mediated environment from that of reality, interpreting the virtual input as though it were from the real world (Chertoff, Schatz, McDaniel & Bowers, 2008). Therefore, the efficacy of these devices as instructional tools hinges on their ability to induce perceptions of presence for science learners of all ages, backgrounds, and contexts.

Most research in this area has explored how the design or usability of virtual environments play a role in inducing presence (Fowler, 2015; Papachristos, Vrellis, Natsis, & Mikropoulos, 2014; Seo & Kim, 2002; Tanaka, 2004; Tromp, Steed, & Wilson, 2003; Whitelock, Romano, Jelfs, & Brna, 2000), however there is a dearth of information on the attributes of the users influencing their perceptions of presence. Witmer and Singer (1998) hypothesized that experiences of presence in virtual environments may be related to a user's selective attention, or "the tendency to focus on selected information that is meaningful and of particular interest to the individual" (p. 226). This idea is bolstered by research relating one's attention to certain information based upon personal assessments of meaningfulness (Triesman, 1963; Triesman & Riley, 1969). A study by Freeman, Avons, Pearson, and IJsselestijn (1999) found "content-related attributes such as interest" contribute to presence (p. 12). In the same study, they also demonstrated that prior experience in rating presence in virtual realms sensitized these users and enhanced their rating of presence when surveyed. More recent work has shown immersion to be greater in individuals who quickly adapt to and are able to concentrate within the virtual environment (Witmer, Jerome, & Singer, 2005).

An area unexplored by current research are K-12 students and their perceptions of virtual presence during 3-D HE VR experiences. Initial studies explored the affordances of 3-D VR technologies for military preparation (Ludvigsen, & Fjuk, 2001) which has developed into medical training (HsiuMei & ShuSheng, 2011; Thacker, 2003) and university level sciences (Eriksson, Linder, Airey, & Redfors, 2014;), namely chemistry education (Coleman & Gotch, 1998; Limniou, Roberts, & Papadopoulos, 2008; Merchant, Goetz, Keeney-Kennicutt, Cifuentes, Kwok, & Davis, 2013; Merchant, Goetz, Keeney-Kennicutt, Kwok, Cifuentes, & Davis, 2012; Özdilek & Calis, 2010; Stull, Barrett & Hegarty, 2013). In analyses by Krange, Fjuk, Larsen, and Ludvigsen (2002), they found few 3-D VR learning environments specifically designed for K-12 students. A recent meta-analysis by Hew and Cheung (2010) on the use of 3-D immersive virtual worlds in K-16 settings found that most studies were conducted at the polytechnic and university level.

In computer-based and technology-enhanced learning environments, adults differ greatly compared to adolescent learners in their ability to engage in self-regulated learning (SRL). Research in this field indicates this is due to adults possessing greater prior knowledge (Moos & Azevedo, 2008; Taub, Azevedo, Bouchet, & Khosravifar, 2014), higher self-efficacy (Moos & Azevedo, 2009), and/or better metacognitive strategies (Greene, Moos, & Azevedo, 2011). This is an important distinction between these groups as engaging in ineffective micro-level SRL processes in these environments may greatly impede learning (Greene, Moos, & Azevedo, 2011). Conversely, intrinsic motivation was found to be a strong factor influencing SRL (Deci and

Ryan, 1985; Zimmerman, 2008). When students fail to benefit from learning in computer-based or technology-enhanced learning environments, it is most often due to a lack of SRL skills, knowledge, or motivation (Greene, Moos, & Azevedo, 2011). Therefore, adolescent and younger learners, lacking in developed SRL skills, rely on the VE to provide SRL scaffolding and support to minimize frustration and distraction while using 3-D VR technology (Virvou & Katsionis, 2008). Students reported more intense experiences of virtual presence when support devices for help seeking were integrated into the VE (Schrader & Bastiaens, 2012). Moreover, in seminal work by Malone and Lepper (1987), students' intrinsic motivations in any learning situation were influenced by challenge, curiosity, fantasy, and control. Even the perception of control, not actual physical control, was found to be significant for mediating intrinsic motivation. Therefore, for children, even the illusion of control and realism may create powerful effects on motivation and learning. Research by Park, Moreno, Seufert, and Brüken (2011) discovered that content that was non-redundant and interesting, even in a low-load (narrative-based) format, resulted in the most effective learning outcomes for sampled students in the VE.

When comparing affective and cognitive states between children and adults, intellectual development underpins this difference. Piaget (1962) hypothesized there were four sequential stages of intellectual development marked by specific hallmarks of cognitive growth: sensorimotor (sensory experimentation at 0 to 2 years), preoperational (use of symbols at 2 to 6 years), concrete operational (logical, concrete thought at 7 to 12 years), and formal operational (abstract thought at 12 years to adulthood). He theorized during cognitive development children actively construct knowledge via development of schemas (mental representations) where information is either assimilated to fit with existing schemas or instead the schema is modified (accommodated) to fit with new information (Southwell, 1998; Wadsworth, 1996). Piaget

(1971) contended that mental development, initially governed by maturation (genetic factors) will yield to experiential input (environment) over the lifespan. In measuring students' intellectual competence, chronological age should not the determining factor, but rather their developmental stage (Southwell, 1998). Because presence relies on the "user's ability to perceive virtual information within these remote settings directly as an extension of their own experiences and senses" (McCreery et al., 2013, p.1635), cognitive ability may play a critical role in a user's perceptions of presence.

Cognitive development invites the question of the efficacy of 3-D, VR environments on K-12 student learning. Bouta and Retalis, (2013) have shown 3-D, VR technology benefits primary students in their understanding of science concepts. Stull, Barrett, & Hegarty (2013) theorized that this is due to the ability of 3-D VR technologies to provide immersive engagement to the user. In addition, 3-D virtual technologies can provide a "wide range of experiences, some of which are impossible to try in the real world because of distance, cost, danger or impracticability" (Chittaro & Ranon, 2007, p.9). In this case, teaching the human heart is of particular interest given its complex structure, sophisticated relationships with other organ systems, and its importance to overall health (Allen, 2010; Dwyer, 1978). We know, for example that the lifetime risk of developing heart failure is one in five for Americans aged 40 years (Roger et al., 2002), creating an incredibly costly and enormous burden on U.S. health care systems (McMurray & Pfeffer, 2005). Patients typically possess a minimal understanding of the heart (van der Wal, Jaarsma, Moser, Veeger, van Gilst, & van Veldhuisen, 2006) which can complicate treatment and prognoses. In North Carolina, curriculum standards on the heart are found throughout the grade bands that include elementary, middle and high school (NC Essential Standards, 2010). Nevertheless primary students (Allen, 2010), secondary students (Nuñez &

Banet, 1996), science teachers (Yip, 1998), and medical students (Badenhorst, Mamede, Hartman & Schmidt, 2015) all hold misconceptions about the heart and its functions. As cardiac anatomy and physiology becomes embedded into interdisciplinary curricula, the demand for viable instructional options to effectively teach the heart is increasing (Raikos & Waidyasekara, 2014). In training studies, medical students have reported being able to visualize the heart in real-time improved their comprehension of heart sounds (Youn & Sanghvi, 2015) and improved their ability to perform in-hospital cardiopulmonary resuscitation (CPR) during a simulated cardiac arrest with haptic feedback (Abella et al., 2007). Within the body of current research in 3-D HE VR technology, these types of instructional tools have made in-roads in student engagement in learning science (Bulu, 2012; Jacobson, 2006; Dalgarno & Lee, 2010), and in learning about the human heart (Chen, Lin, Li, Hseih, Du, & Chen, 2015; Silén, Wirell, Kvist, Nylander, & Smedby, 2008).

Significance of the Study

The reviewed literature that follows suggests that perceptions of presence varies among individuals when exposed to similar or identical virtual environments (Baumgartner, Speck, Wettstein, Masnari, Beeli & Jäncke, 2008; Ling, Nefs, Brinkman, Qu, & Heynderickx, 2013; Wallach, Safir, & Samana, 2009). This study's rationale is to explore possible covariates, namely a user's level of cognitive development, and its influence on perceptions of virtual presence. Hypotheses expected in this research is the level of cognitive development as a factor that influences individuals' experiences of virtual presence and learning science content in virtual realms. It is expected that both 6th and 9th grade groups will demonstrate improved understanding of cardiac form and function after treatment, however 9th grade students may out-perform 6th grade students on tests of cardiac knowledge based upon their Piagetian development. In particular in the areas of spatial and rotation, mental functions may aid learning in VE. However, both 6th and 9th grade groups are expected to undergo similar learning trajectories from active, constructive and interactive activity. This will help inform the use of 3-D HE VR technology in the K-12 classroom that promotes engagement and learning appropriate to student level and cognitive ability.

Research Questions

Research Question 1 – Does a 3-D, haptic-enabled virtual reality technology experience promote understanding of cardiac anatomy and physiology for 6th and 9th grade students?

a. Are there increases in understanding of cardiac anatomy and function?
b. In what ways does 3-D, HE VR experiences influence understanding of cardiac circulation?

Research Question 2 – Are there differences in 6th and 9th grade science students' perceptions of presence when engaged in 3-D, haptic-enabled virtual reality instruction?

Research Question 3 – Is there a relationship between 6th and 9th grade students' cognitive dimensions[1] and perceptions of presence?

a. What is the relationship between students' scores on the Inventory of Piaget's Developmental Tasks (IPDT) constructs[2] and subtests[3] and perceptions of presence?
b. What is the relationship between students' scores on the Inventory of Piaget's Developmental Tasks (IPDT) cognitive classifications[4] and perceptions of presence?

Research Question 4 – Does 3-D, haptic-enabled virtual reality technology influence learning for 6th and 9th grade students?

a. What type of questioning, related to students' learning of cardiac content[5], do students report prior, during and after instruction?

b. Are there differences in questioning between 6th and 9th grade students?

c. Is there a relationship between students' questioning and perceptions of presence?

d. Is there a relationship between students' questioning and students' scores on the Inventory of Piaget's Developmental Tasks (IPDT)?

Research Question 5 – Is there a relationship between 6th and 9th grade students' understanding of cardiac anatomy and physiology and perceptions of presence?

a. What is the relationship between students' scores on a test of cardiac knowledge and student's questioning?

b. What is the relationship between students' scores on a test of cardiac knowledge and students' perceptions of presence?

c. What is the relationship between students' scores on a test of cardiac knowledge and scores on the Inventory of Piaget's Developmental Tasks (IPDT) constructs[2] and subtests[3]?

d. What is the relationship between students' scores on a test of cardiac knowledge and scores on the Inventory of Piaget's Developmental Tasks (IPDT) cognitive classifications[4]?

CHAPTER 2: Theoretical Background

Review of the Related Literature

Presence and Immersion

This study builds on previous work related to presence, which is defined as participation (Sheridan, 1992) or perception of being in another environment (Slater & Wilbur, 1997). Presence may be defined in a variety of contexts, such as social (Daft & Lengel, 1984), media (Lee, 2004), and gaming (Lombard & Ditton, 1997). Each dimension of presence has its own robust field of study. This research will focus on the environmental and personal aspects of presence defined as virtual presence. This type of presence specifically couples involvement and immersion to have the user "perceive that they are interacting directly, not indirectly or remotely, with the environment" (Witmer & Singer, 1998, p.227). According to Whitner and Singer (1998), both involvement and immersion are necessary for experiencing presence. Involvement is mediated by the users' ability to control the virtual environment and hold the user's attention within the virtual realm. Therefore, the display and hardware of technology generating virtual environments should ensure the user is comfortable wearing and using the equipment; if such hardware is cumbersome or confining, the users involvement in the virtual environment will diminish considerably (Witmer & Singer, 1998).

Immersion gauges the quality of the virtual environment to the real world. Continuous or deep immersion relies upon encompassing sensory engagement and realistic features within the virtual realm. Steuer (1992) describes the sensory experience as shaping how real the environment appears to the user. Among the senses, visual information may most strongly influence presence (Witmer & Singer, 1998) yet research into haptics has found that body interactions yielded an increased sense of presence for the user (Slater & Steed, 2000). There is even evidence from a study by Biocca, Kim and Choi (2001) that participants reported haptic illusions in the absence of stimuli from the sensory channel interface due a profound sense of immersive presence. A study by Reiner and Hecht (2009) has shown that a visuohaptic presentation (i.e. merged visual and tactile sensory information) of a razor blade generated an object-presence illusion causing participants to move their hand more slowly and applying less force as compared to an identical task without the razor representation. Another study by Weir et al., (2013) found when participants placed their hands in a virtual fire (BurnAR), they reported involuntary warming sensation and a smell of smoke. Due to the profound sense of immersive presence users experience within these VE, they may also invoke negative affective states like fear and anxiety (Dede, 2009), thus underscoring the importance of understanding users varying cognitive dimensions and presence perceptions in the proper and ethical use of this technology.

Hardware of 3-D HE VR Technology

According to Limniou, Roberts, and Papadopoulos (2008) there are four hardware strategies to create a 3-D VR display, although each has advantages and disadvantages. Desktop systems employ a mouse, keyboard and a traditional monitor to produce a 3-D like effect are less expensive yet provide a less than ideal environment for immersion. Head mounted displays require the user to wear headphones and headgear to create a 3-D VR effect, although becoming cumbersome for the user over extended periods of time (Lee, Cherng, & Lin, 2004). Immersive project technology systems use holograms projected on surfaces to create a 3-D VR environment that may be shared with more than one user at a time. Although immersive and ideal, these systems require advanced hardware and large dedicated spaces that are costly and immobile. The use of a stereoscopic display provides the viewer two different images of the same object, positioned for each eye to receive visual information for (binocular vision) depth and perception.

To avoid distortion and eyestrain, the user should be an optimum distance and angle from the system. Stereoscopic displays are of particular interest in presence research. A study by Price, Lee, Subbarao, Kasal, and Aguilera in 2015 provided 2-D and stereoscopic images of the Milky Way galaxy to museum visitors and assessed their knowledge of its structure and function. Controlling for demographics between both groups, results indicated there were short-term learning gains in both the 2-D and stereoscopic groups yet only the stereoscopic group exhibited long-term learning gains (p. 1137). However, this is balanced with other studies demonstrating that student learning with VR technology is short-lived as long term conceptual change has been unsuccessful (Neulight, Kafai, Kao, Foley, & Galas, 2007).

One major advancement in developing presence is in the hardware design of these devices. Early studies assessing presence found using multiple sensory inputs (e.g. 3-D coupled with head tracking) were associated with higher presence ratings (Arsenault & Ware, 2004; Freeman et al., 1999). Therefore, more technologies are progressively incorporating visuohaptics. Haptic feedback has been shown to provide a more immersive experience for the student, however the degree to which haptic feedback influences learning is not yet clear (Jones, Minogue, Tretter, Negishi, & Taylor, 2006). According to a meta-analysis by Minogue and Jones in 2006, globally “there is little written about how adolescents perceive objects through the sense of touch” (p.324). However, the adoption of haptic-enabled technology in mobile gaming is rising geometrically, where touch feedback technology “creates fun and compelling (gaming) experiences" (“Computer Peripherals”, 2015, p.143). Despite the demonstrated benefits of 3-D HE VR technologies independently, metrics for evaluating virtual presence within systems that couple all three sensory inputs remain rudimentary.

According to work by Jones et al. (2015), “augmented experiences that include sight, sound, movement, and haptics all contribute to a more realistic virtual environment” (p. 2). Since 3-D HE VR systems are crafted to couple involvement with deep immersion into a simulated world, it is hypothesized that these tools have a great potential to induce presence for the user (Witmer & Singer, 1998). Presence often serves as a proxy for the potential positive transfer of skills or knowledge learned in a VE to the real world (Mestre & Fuchs, 2006). Research by Osberg (1997) suggests that multi-sensorial input can be challenging for students, especially for those with disabilities. Since the 1990s, the potentiality of these nascent 3-D HE VR systems had been described to significantly “contribute to learning and reasoning in mathematics and science education” (Pea, 1993, p.60). However, the affordances of instructional technologies that combine 3-D rendered images coupled with haptic feedback for younger learners is largely unknown.

Review of Literature Related to the Problem

Stages of Cognitive Development

Cognitive abilities mature throughout one’s lifespan along a progressive continuum of neural development continuing from childhood, through adolescence and into adulthood. Piaget (1962) postulated there are four major phases of sequential intellectual development, each highlighted by newly developed cognitive abilities. Sensorimotor, or cognitive experimentation, followed by preoperational cognitive development where imagination, memory and symbolism develop mid-childhood. This is followed by a concrete operational stage where individuals cultivate logical reasoning and a growing discernment of what is reality from fantasy. From adolescence and into adulthood is according to Piaget the final stage of cognitive development where formal operational processing occurs, abstraction of intangible concepts is achieved, and experience over instinct mediates how one views the world beyond themselves.

As age is an inadequate proxy for development, assessments are required to determine Piagetian cognitive development. There are a number of valid interviews and inventories that have been designed to explore the major problem areas of conservation, images, relations, laws, and classification (Patterson & Milakofsky, 1980). Piagetian assessments typically involve "language, logical reasoning, moral judgments, and conceptions of time, space, and number" (Southwell, 1998, p. 4). Other Piagetian concepts included in these assessments involve moral judgment, conservation, and spatial operations (DeLisi, 1979). The difficulty of science concepts can be categorized in terms of students' abilities to perform Piagetian tasks (Southwell, 1998). Piagetian inventories have been empirically validated with all age and ability groups including primary students (Bakken, Thompson, Clark, Johnson & Dwyer, 2001), adults in science courses (Bender & Milakofsky, 1982; Coleman & Gotch, 1998) and students with disabilities (Riley, 1989).

Cognitive Development and the Prefrontal Cortex

Neuroimaging research indicates that the prefrontal cortex, the region of the brain most closely associated with planning and judgement (Fuster, 2008) is functional at 4 years of age, yet organizes into its full potential through later development (Satoshi, 2008). This closely mirrors Piaget's findings of intellectual development, suggesting changes in the prefrontal cortex through time lead to more robust understandings of abstract concepts and perceptions of reality (Casey, Galvan, & Hare, 2005; Casey, Giedd, & Thomas, 2000). A study by Baumgartner et al. (2008) has demonstrated that the activation of a highly specific neural network mediates the experience of presence in adults in VEs; this absence of activity due to underdeveloped prefrontal regions may contribute to an increased experience of presence among children in identical VEs.

In addition to planning and judgment, the prefrontal cortex has also been shown to be related to personality traits (DeYoung et al., 2010). In turn, personality has long been strongly correlated with interest (Ackerman & Heggestad, 1997) which was previously discussed as a cofounding factor in presence (Freeman et al., 1999; Whitmer & Singer, 1998). A study by Weibel and Wissmath (2011) explored the relationship between presence and flow, a construct related to involvement in a gaming environment. Despite their similarities, a factor analysis demonstrated they are distinct constructs with little common variance, with flow focused on specific tasks and presence as overall immersion in the VE. Weibel and Wissmath argue "presence and flow are positively affected by motivation and immersive tendency and in turn influence enjoyment and performance" (p. 11). Overall, perceptions of presence are dependent on the immersive characteristics of the VR system and may be influenced by contextual and psychological factors (Mestre, 2015).

Contextual Factors Influencing Presence

The contextual factors within presence research have shown that individuals experience different levels of presence even when exposed to the same virtual environment (Ling, Nefs, Brinkman, Qu, & Heynderickx, 2013). In one study, individuals with high empathy and active imaginations reported greater presence compared to other participants in identical virtual realms (Wallach, Safir, & Samana, 2009). A study by Prokop, Prokop, Tunnicliffe, & Diran (2007) demonstrated children's representational drawings of animals and their internal organs; drawings were significantly different in the presence of preserved specimens (3-D) as compared to those from 2-D drawings. They proposed these differences were also due to children's motivation to more carefully observe realistic representations of objects such as three-dimensional animals. These findings may inform how children's visual conceptions can be influenced by these factors in VR settings. Relatively little is known about the influence of interest or prior knowledge and perceptions of presence.

Psychological factors stem from neural imaging research indicating children and adults experience and process virtual presence differently. Adults in virtual environments use self-reflection and experience, cognitive constructs associated with prefrontal regions that are under-developed and inactive in children (Baumgartner et al., 2008). This work suggests that children may experience greater virtual presence due to an inability to self-evaluate the stimulated environment vis-à-vis physical reality. This suggests an individual's age and level of cognitive development may affect perceptions of presence; yet there is a dearth of research exploring developmental aspects to perceptions of presence. The goal of this research was to examine how cognitive development influences users' perceptions of presence for experiences in 3-D HE VR technology. Previous research has shown that spatial processing skills are an important component in cognitive development. A study by Osberg (1997) found that students leveraged their experience in multi-perceptual learning environments to aid in developing spatial concepts and relationships.

Other psychological factors in presence research have shown that increased spatial ability positively influenced short-term learning gains (Price, Lee, Subbarao, Kasal, & Aguilera, 2015) in 3-D VR environments. A study by Barrett and Hegarty (2014) suggested that individuals with low-spatial abilities learn less in VEs than those with high spatial-abilities. They hypothesize individuals with greater spatial acuity may be more cognitively equipped to process stereoscopic visualization. Another study by Modjeska and Chignell (2003) found users who scored in the lowest quartile of spatial ability had significantly lower performance in a 3-D VR environment. These findings may relate to established research showing the neural architecture segregating activities into specific geographic areas for optimal neural processing. Within the anterior section of the brain, the frontal lobe houses centers known for speech, language processes and executive functions that include working memory, planning, and decision making (Fuster, 2008). The prefrontal cortex is a highly evolved structure that regulates behavior when presented with vivid sensory inputs that are either rapidly changing or unique to one's prior experience (Miller & Cohen, 2001). Therefore, this region activates when the body is inundated with sensory input to make meaning and judgements of novel or unique experiences. Notably, this region develops with age and experience (Satoshi, 2008) which may provide additional insight as to why adults experience presence differently than children (Baumgartner et al., 2008; Spronk & Jonkman, 2012). Although there are strong connections between neuroscience and presence, there is little research connecting these two domains of knowledge (Sanchez-Vives & Slater, 2005) or exploring cognitive development, with presence (Jones et al., 2015). Only recently has the progression of cognitive development theorized by Piaget been verified using Piagetian tasks with children and adults using functional magnetic resonance imaging (fMRI) (Leroux et al., 2009).

Early work in gauging presence suggested theoretical factors that contribute the perception of presence including body movements (Slater, Steed, McCarthy, & Maringelli, 1998), sensory stimulation (Held & Dulach, 1992), and sensory feedback (Sheridan, 1992). Witmer and Singer (1994) grouped aspects of presence using empirical data sourced from participants in virtual environments using a presence questionnaire. From that information, Witmer and Singer (1998) refined aspects of presence into four constructs (which they called factors) of control, sensory, distraction, and realism. The authors indicated that factors across categories would interrelate, provided they “may exert their influences on presence by affecting either involvement, immersion, or both. We speculate that control factors may affect immersion but not involvement, while Realism Factors should affect involvement but not immersion. We hypothesize that Sensory Factors and Distraction Factors should affect both immersion and involvement” (p. 228). Table 1 provides these factors and aspects related to presence rated by the user (Witmer & Singer, 1998, p.299).

Table 1

Four Factors Hypothesized to Contribute to a Sense of Presence

Control Factors	Sensory Factors	Distraction Factors	Realism Factors
Degree of control	Sensory modality	Isolation	Scene realism
Immediacy of control	Environmental richness	Selective attention	Information consistent with the objective world
Anticipation of events	Multimodal presentation	Interface awareness	Meaningfulness of experience
Mode of control	Consistency of multimodal information		Separation anxiety / disorientation
Physical environment modifiability	Degree of movement perception		
	Active search		

Note: Constructs backing Presence Questionnaire designed by Witmer & Singer (1998).

It has become apparent that there are few comprehensive assessments that measure the impact of 3-D, HE VR applications on learning. According to Sanchez-Vives and Slater (2005) outside of measuring true transfer from virtual worlds to reality, a more resourceful approach is to measure presence, as this concept applies across content and non-specific applications. In 2015, Jones et al. adapted the presence questionnaire developed by Whimer & Singer (1998) to evaluate presence in 3-D, HE, VR environments. This survey included items within the four factors of presence to specifically address presence during a 3-D, HE, VR investigation using the zSpace® platform.

Affordances of 3-D HE VR Technology for Science Teaching

In this paper, affordances are defined as the relationship between the properties of an educational intervention (e.g. technology) and the facilitation of learning given specific characteristics (age, cognitive development) of the learner (Dalgarno & Lee, 2010; Kirschner, 2002). Because 3-D HE VR technology strives to replicate the real world, there is a potential for as Ruzic (1999) describes as "individualized, interactive and realistic learning that makes virtual reality a tool for apprenticeship training, providing a unique opportunity for situated learning" (p. 188). Based upon the work of Lave and Wenger (1991) in situated learning, numerous authors have described how 3-D HE VR technologies can replicate the apprenticeship model virtually to engage the learner in legitimate peripheral participation through co-participation with the technology (Bronack, Riedl & Tashner, 2005; Chittaro & Ranon, 2007; McLellan, 2004). Virtual situated learning may provide a powerful opportunity for novices to engage in complex, intricate or potentially hazardous training situations with no repercussions on wasting materials or live specimens (Hempe & Rosmann, 2015; Prokop, Prokop, Tunnicliffe, & Diran, 2007; Shi, Zhang, & Shao, 2008;), patients (Lewis et al., 2011) or to the user (Xu, Lu, Guan, Chen, & Ren, 2014); yet are more effective than traditional learning experiences for biological science (Kinzie, 1993), chemistry (Coleman & Gotch, 1998; Limniou, Roberts, & Papadopoulos, 2008; Merchant, Goetz, Keeney-Kennicutt, Cifuentes, Kwok, & Davis, 2013; Merchant, Goetz, Keeney-Kennicutt, Kwok, Cifuentes, & Davis, 2012; Özdilek & Calis, 2010; Stull, Barrett & Hegarty, 2013), or practicing medicine (Andersen, Mikkelsen, Konge, Cavé-Thomasen, & Sørensen, 2016; Ruthenbeck & Reynolds, 2015; Thacker, 2003; Zhao, Kennedy, Kumiko, Pyman, & O’Leary, 2011). The majority of the research studies done on 3-D HE VR as instructional tools have been done in medicine and chemistry, for applications that are not easily experienced at the macroscale. However, other disciplines are beginning to incorporate 3-D HE VR experiences in subjects at a variety of student ages including middle grade engineering (Klahr, Triona, & Williams, 2007), elementary earth science (Sun, Lin, & Wang, 2010) and mathematics education (Sarama & Clements, 2009).

Computer-enhanced learning environments that combine vivid and interactive visualization are hypothesized to promote active processing through a reduction of extraneous cognitive processing in lieu of the learner generating their own mental pictures, resulting in reduced comprehension due to a decrease in cognitive resources available for essential and generative processing (Schwamborn, Thillmann, Opfermann, & Leutner, 2011). Research exploring VR training simulations have seen lower cognitive load (CL) demand than compared to traditional instruction (Andersen et al., 2016), which may prove useful for teaching and learning given the established empirical relationship between lower CL and cognitive retention for science simulations in computer-enhanced learning environments (Lee, Plass, & Homer, 2006).

There is developing recognition of virtual presence as a field of research since users may become more engaged in learning activities due to the realistic contexts these systems provide to “design meaningful learning activities in immersive virtual learning environments” (Cho, Yim, & Paik, 2015, p.70). This is of particular interest in education as prior studies suggest there is a correlation between perceptions of increased presence and student learning gains (Hedley, Billinghurst, Postner, May, & Kato, 2002; Mikropoulos, 2006; Childers & Jones, 2015). Research by Chi (2009) has established a framework for identifying and categorizing learning activities undertaken by a user that is applicable to learning in VE technologies. VR environments are inherently non-passive, where the user must make choices or actions to advance through presented content. Students can describe the type and depth of their learning activity through open-ended questioning which may subsequently be classified as active (activation of existing knowledge, encoding new information), constructive (assimilating or accommodating new knowledge) or interactive (self-construction, sequential or co-construction of knowledge). This framework focuses on understanding how different learning activities can benefit or foster learning (Chi, 2009). Tests of content may only determine students' understanding of a content domain. Understanding provides a snapshot of the product of new knowledge garnered from a teaching experience, yet does not provide insight to the learning processes occurring during the session. Incorporating Chi's (2009) framework through student open questioning will contribute data to students' learning experiences when engaged in a 3-D, HE VR environment. According to Freitas and Neumann (2009), the use of these tools will present new challenges for lesson planning, classroom structure, and science content (p. 343). Comprehending how users' perceptions of presence differ can provide important information regarding how these technologies may be implemented in the K-12 science classroom and ultimately increase student interest in science and understanding of scientific processes and procedures.

CHAPTER 3: Methodology

Research Design

This study investigated the relationship between 6th and 9th grade students' cognitive dimensions on perceptions of virtual presence and sought to further the contemporary understanding of virtual presence and how it varies among individuals given an identical 3-D HE VR experience. In addition, this study explored the students' learning gains and activities prior to, during and after 3-D HE VR instruction on cardiac anatomy and physiology. Using the Campbell and Stanley (1963) research design notation, where *X* represents the exposure of a participants to a measurable experimental variable or event and *O* refers to the process of observation and measurement, the research design is as follows.

Experimental O_1 X O_2

Within the O_1 condition participants took an Inventory of Piaget's Developmental Tasks (IPDT) task and pre-test of cardiac knowledge. The treatment condition consisted of participants using the 3-D, haptic-enabled virtual reality system where student engaged in open-ended questioning to elicit their cognitive engagement in learning activities. The O_2 condition consisted of participants taking a presence survey and a content post-test on cardiac knowledge. Participants and assessments are described in the sections below.

Participants

Participants were volunteers from urban and rural counties in North Carolina. Students from 6th and 9th grades were invited to participate. These grade levels were selected based upon Piaget's levels of cognitive development (1962) to sample students in a two distinct phases of Piagetian development, children in the concrete operational stage (6th grade) and adolescents in the formal operational stage (9^{th} grade). Students were recruited for this study through science and health classes via personal visits to their respective schools. Seventy-five 6^{th} grade students participated from a public middle school in an urban setting. Seventy-six 9^{th} grade students participated from an urban (*N*=50) and a rural (*N*=26) public high school. Schools were matched by socioeconomic status (SES), race, ethnicity and gender. The pool of 6^{th} grade participants included 29 males and 46 females, who identified as White (*N*=42), African American (*N*=24), Asian (*N*=8), Native American or American Indian (*N*=8), Hispanic, (*N*=16), non-Hispanic (*N*=59), and Native Hawaiian or other Pacific Islander (*N*=3) with a mean age of 11.22 years (Median=11, Mode=11). The pool of 9^{th} grade participants included 32 males and 44 females who identified as White (*N*=50), African American (*N*=19), Asian (*N*=7), Hispanic, (*N*=22), non-Hispanic (*N*=54), and Native American or American Indian (*N*=5), with a mean age of 14.26 years (Median=14, Mode=14). Students had the opportunity to select more than one racial affiliation which was accounted for in total numbers. Students with consent who completed three assessments (i.e. pre and post cardiac content tests, inventory of Piaget's developmental tasks, and presence survey) were included in the study.

Equipment

This study utilized an instructional tool whose hardware included three dimensional (3-D) images with haptic-enabled (HE) feedback within a virtual reality (VR) system. The zSpace® platform consists of a central processing unit (CPU), a 24 inch high definition liquid crystal (1080p, 120Hz) 3-D stereoscopic display screen complete with built-in tracking sensors to track the viewing angle of the user, a 3-button stylus with integrated haptic technology and infrared LEDs for manipulating interactions within the virtual reality space, and a set of polarized eye-glasses with reflective sensors to track head and body movement in real-time (zSpace®, 2015).

Figure 1 shows the components of the zSpace® system, a close-up view of the 3-D glasses, the 3-button haptic enabled stylus, a close-up view of the head tracking interface, and an individual engaged with the hardware and software of the system during the training session.

The zSpace® system

Passive Polarized Eyewear

The haptic-enabled stylus

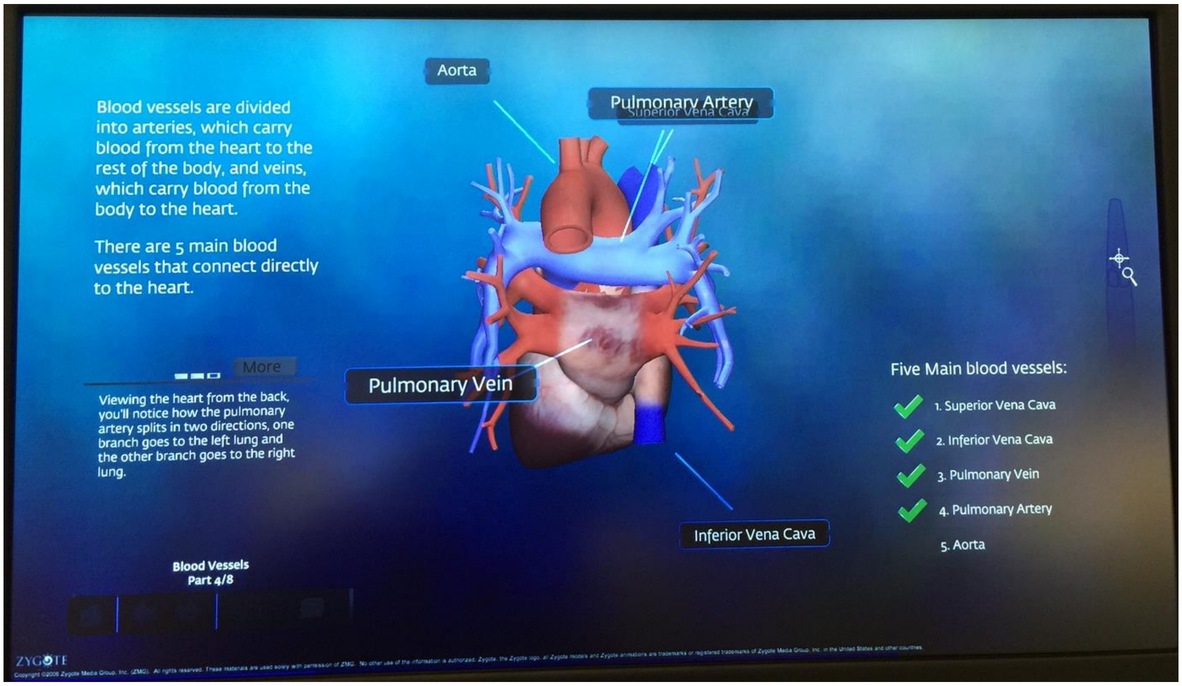
A user with zSpace®

Head tracking interface

Figure 1. The zSpace® System. (Hite, 2016a).

Instruction/Treatment/Intervention

Participants took the IPDT (see **Appendix A**) and a content pre-assessment on heart anatomy and physiology (see **Appendix B**) prior to instruction with the technology. In the first session (training) with the zSpace® system, students were given 40-60 minutes to explore the hardware and software of the technology. Individually and in pairs, participants practiced moving, rotating, scaling and dissembling objects using the haptic-enabled stylus, wearing the 3-D eyeglasses, and navigating the virtual environment. During this session, participants had the opportunity to use the system to virtually dissemble a robotic arm, examine butterflies, and dissect various objects (e.g. plants, animals, molecules, microbes, planets, motors, engines, etc.) of their choosing. The second session (treatment) each subject individually interacted with the zSpace® system. Prior to specific instruction on heart anatomy and physiology, students were prompted to write one question about the structure and function of the human heart (see **Appendix C**). Once completed, students were presented with instruction on cardiac anatomy and function (see **Appendix D**) called zAnatomy®. This software application included eight scripted slides providing rich images of the cyclic contraction of the human heart while mirroring the heart-beat via haptic vibrations (pulsation) in real time. Figure 2 is a screenshot of zAnatomy® and Figure 3 shows the haptic feedback feature in zAnatomy®.



Blood vessels are divided into arteries, which carry blood from the heart to the rest of the body, and veins, which carry blood from the body to the heart.

There are 5 main blood vessels that connect directly to the heart.

Viewing the heart from the back, you'll notice how the pulmonary artery splits in two directions, one branch goes to the left lung and the other branch goes to the right lung.

Five Main blood vessels:

✓ 1. Superior Vena Cava
✓ 2. Inferior Vena Cava
✓ 3. Pulmonary Vein
✓ 4. Pulmonary Artery
5. Aorta

Figure 2. A screenshot of Part 4/8 of zAnatomy® on zSpace® (Hite, 2016b).

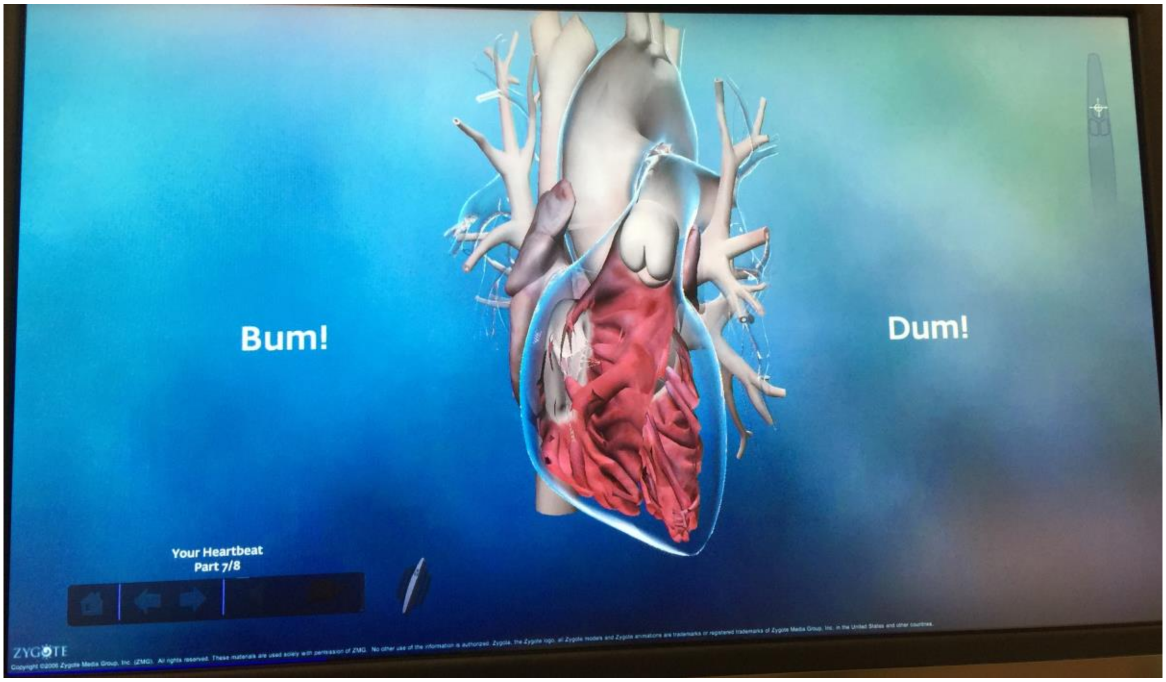


Figure 3. A screenshot of Part 7/8 of zAnatomy® on zSpace® (Hite, 2016c).

At the conclusion of 25-30 minutes of instruction, students were asked a second time to write a question on the topic of cardiac form and function (**Appendix C**). After asking their second question, students engaged in a free-choice environment that allowed them to explore the human heart (zExperience®). In this module, students were given a haptic-enabled heart that could be labeled with terminology, made transparent, and closely examined with the use of a user-directed virtual camera. Participants explored the heart at their own pace where they experienced touch feedback through haptic pulsation, viewed labels and vocabulary, manipulated the heart rate and its position on the screen. Figure 4 is a screenshot of the zExperience® heart on the zSpace® system and Figure 5 demonstrates a user interacting with the heart in zExperience®.

Figure 4. A screenshot of the heart in zExperience® on zSpace® (Hite, 2016d).

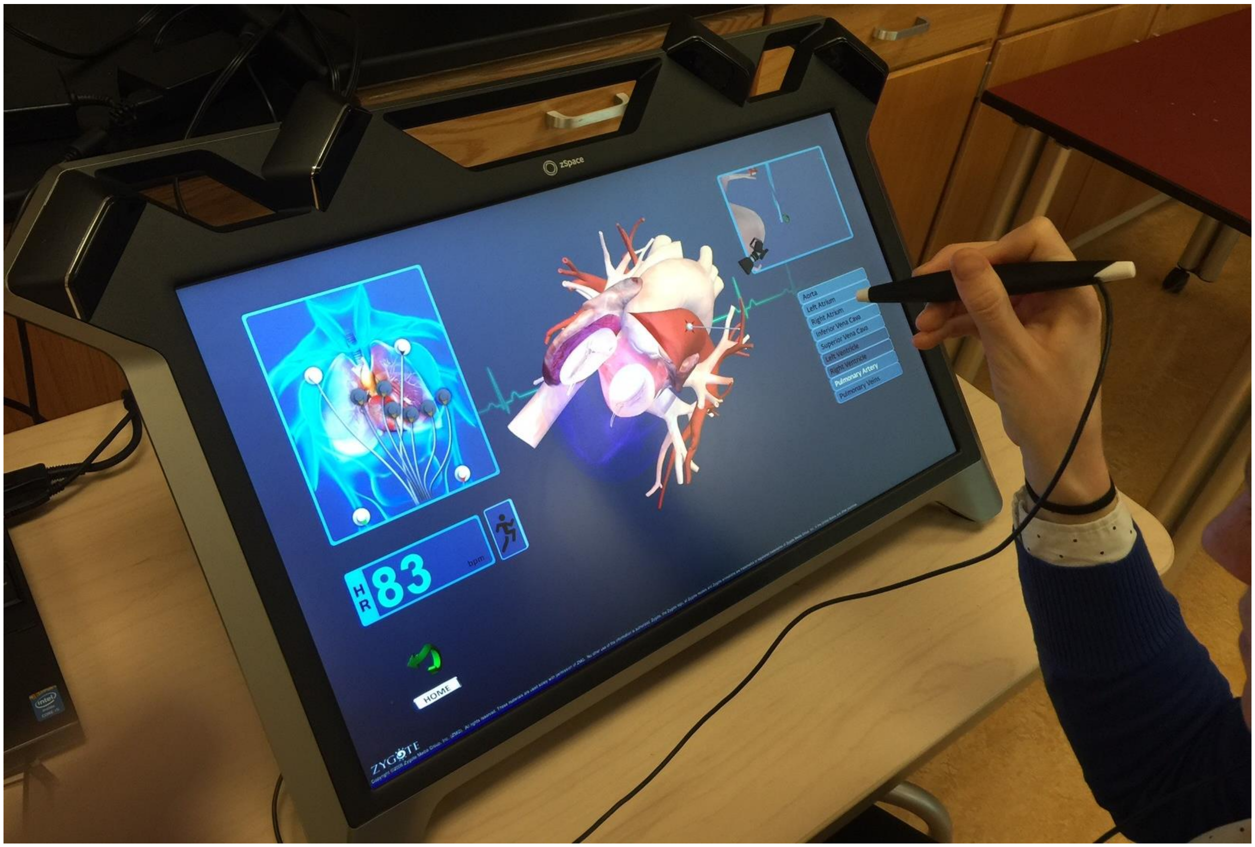


Figure 5. A user interacting with the heart in zExperience® on zSpace® (Hite, 2016e).

Upon completion of 15-20 minutes using zExperience®, participants wrote the third and final question on cardiac form and function (**Appendix C**). Immediately after completing their experience on the zSpace® system, participants answered the presence survey including of sixty-two 6-point likert scale items that contributed to their virtual presence (e.g. control, sensory factors, distraction, and realism) (see **Appendix E**). After 3 days (9th grade students) and one to two weeks (6th grade students), study participants were post-tested on cardiac anatomy and physiology concepts related to their experiences in the zSpace® treatment (**Appendix B**). For middle grade students who were delayed in post-testing, participants were given 2 minutes on the zSpace® Experience® application to remind them of the human heart's structure and vocabulary. Open-ended questions (1 and 30) of the student cardiac content assessment was scored with a rubric and selected response questions were scored with an answer key (questions 2 through 29) (See **Appendix E**).

Assessments and Data Analysis

Test of Cardiac Knowledge. A 30 question assessment (28 selected response items and 2 open-ended questions) was created by a team of three science educators and influenced by Dwyer's research (1972; 1978) on visual strategies teaching and assessing student understanding of the human heart. The test was structured after Dwyer's (1972) schema of a cardiac visualization test employing a drawing test (p.119), identification test (p.121), terminology test (p.124), and comprehension test (p.128). Items were adapted for testing with younger learners by simplifying and clarifying language of Dwyer's original item (questions 15, 16, 20, 22, 26,) or removing aspects of items that did not directly relate to content presented on the heart during the zSpace® session (questions 1, 5-13). Additional questions were added to assess students' retention of specific concepts introduced in the zSpace® session (questions 2, 3, 4, 5, 14, 18) and exploit the 3-D, haptic and virtual nature of the instruction (questions 17, 19, 21, 23, 24, 25, 27, 28, 29 and 30) (Appendix B). Reliability for the test of cardiac knowledge was completed using Kuder-Richardson (KR) 20 formula as a check of the internal consistency of test items. KR-20 is a reliability measure sensitive to content heterogeneity; the degree in which the test items measure related characteristics (Reynolds, Livingston, & Willson, 2009). It is most applicable for analysis as these two tests were assessing a single homogenous domain of knowledge in a single, untimed test administration. Therefore, it examines the consistency of responses with varying item difficulties among all individual items on each respective test (Reynolds et al., 2009). For the KR-20 analysis, participant answer choices were recorded as 0 (incorrect) or 1 (correct) for each item and totaled. Each test administration, pre-treatment and post-treatment, were evaluated for reliability. Twenty-eight selected response items were given to 151 participants with consent twice (prior to and after the zSpace® treatment). The ρ_{KR20} values were calculated as 0.577 for 6th grade and 0.707 for 9th grade. Table 2 below shows KR-20 values for each test administration.

Table 2

Reliability Data for Four Administrations of a Test of Cardiac Knowledge

	K	∑(pq)	σ^2	ρ_{KR20}
6th Grade				
Pre-test	28	5.20	8.54	0.405
Post-test	28	5.20	18.7	0.749
9th Grade				
Pre-test	28	5.20	11.9	0.583
Post-test	28	5.20	26.0	0.830

Note: Kuder and Richardson Formula 20: Values range from 0 to 1. High values indicate reliability, values <0.90 indicates homogenous test. Value of <0.6 is acceptable for research.

A paired t-test was performed on the students' interval data (selected response questions 2 through 29) to determine significance between pre and post test scores. Correlations using

Spearman’s rank correlation (rho) coefficients were made to determine relationships between students’ (test scores of) cardiac knowledge and student’s presence scores as well as students’ scores on IPDT tasks.

Questions 1 and 30 on the student cardiac assessment were scored using a rubric created by three science educators and informed by Dwyer (1972; 1978) regarding students’ knowledge of the human heart. For question 1, interrater agreement was completed on 60 out of 302 responses, for a total of 86.0% agreement. For question 30, interrater agreement was completed on 60 out of 302 responses, for a total of 87.6% agreement. A Wilcoxin signed-ranks test was performed to evaluate the significance between pre-treatment and post-treatment administrations.

Presence Survey. The presence survey contained questions designed to understand 6th and 9th grade students’ perceived presence during science-based investigations by recording students’ perceptions of control, sensory, distraction, and realism within the virtual environment. The framework of the presence survey was built from Witmer’s and Singer’s presence questionnaire stem questions (1998, p. 232) and other research on students’ perceptions of presence (Childers & Jones, 2015; Jones et al., 2015). Survey items were categorized into the four presence constructs and additional questions were added to each category to reflect the 3-D and HE capabilities of the zSpace® system. A panel of science educators, middle school students, zSpace® educators and computer programmers with specialized knowledge this technology reviewed and refined each item. Study participants were asked to indicate their level of agreement for 61 items related to 4 presence factors: control (“I felt that I was in control of the zSpace® 3-D environment during the session”), sensory engagement (“My sense of touch was highly engaged during the session”), distraction (“The stylus was distracting”), and realism (“I lost track of time during the zSpace® session”) after treatment on zSpace® to learn about the heart. The survey is a Likert scale format from 1-6 (i.e. strongly disagree to strongly agree). The presence survey was taken online or on paper and aggregated using Qualtrics software. Presence statements were analyzed by item and by construct using the Mann-Whitney U test (2-tailed, alpha = 0.005) to ascertain significance between age groups within each construct of control, sensory, distraction, and realism, respectively. Cronbach's alpha was calculated with a reliability value of 0.933, 0.762, 0.769, 0.705 and an overall value of 0.934 for 6th grade student responses and 0.927, 0.776, 0.797, 0.677 for an overall value of 0.953 for 9th grade responses. Values for both groups demonstrate a strong internal consistency of items and responses. Cronbach's alpha was calculated for both groups was 0.944 (*N*=151, for 86 total items). Table 3 shows reliability values for 6th and 9th grade student scores on the presence survey. Correlations using Spearman's rank correlation (rho) coefficients were made to determine relationships between presence scores and IPDT tasks.

Table 3

Reliability Measures (Cronbach's Alpha) by Control, Sensory, Distraction, and Realism Items

Presence Category	6th Grade (*N* =75)	9th Grade (*N* =76)	6th and 9th Grade (*N* =151)
Control Items (*N* = 21)	0.933	0.927	0.930
Sensory Items (*N* = 8)	0.762	0.776	0.768
Distraction Items (*N* = 17)	0.769	0.797	0.781
Realism Items (*N* = 15)	0.705	0.677	0.691
Whole Test (*N* = 82)[a]	0.934	0.953	0.944

Note: $\alpha \geq 0.9$, Excellent; $0.7 \leq \alpha < 0.9$, Good; $0.6 \leq \alpha < 0.7$, Acceptable, $0.5 \leq \alpha < 0.6$, Poor; $\alpha < 0.5$, Unacceptable

[a]Contains items not reported here.

Inventory of Piaget's Developmental Tasks (IPDT). This 72-item selected response inventory is a validated and un-timed individual assessment of Piagetian developmental tasks (Furth, 1970). The assessment included 14 items on conservation (quality, weight, volume, distance), 14 items on images (levels, perspective, movement, shadows), 12 items on relations (sequence, seriation, inference), and 14 items on classification (matrix, symbols, classes, inclusion). Items were scored as correct or incorrect; students demonstrated proficiency in a sub area with a minimum of 75% of questions (three out of four) correct (Patterson & Milakofsky, 1980). Cronbach's alpha was calculated with a reliability value of 0.791 (*N*=18) for 6th and 9th grade student responses. This value shows a strong internal consistency of items and responses. Table 4 shows the relationships between construct areas, subtests and item difficulty on the Inventory of Piaget's Developmental Tasks (IPDT). Correlations using Spearman's rank correlation (rho) coefficients were made to determine relationships between IPDT constructs, subtests and cognitive classifications to cardiac assessment scores, learning activities and presence scores.

Table 4

Inventory of Piaget's Developmental Tasks (IPDT) Cognitive Classifications (by age) and Construct, Subtest

	Classification (*N*=16)	Images (*N*=16)	Conservation (*N*=16)	Relations (*N*=12)	Laws (*N*=12)
Low Range (7-8) (*N*=24)	Matrix Symbols	Movement	Quantity	Sequence Seriation	--
Midrange (9-10) (*N*=24)	--	Levels Perspective Shadows	Weight Distance	--	Rotation
High Range (11-13) (*N*=24)	Classes Inclusion	--	Volume	Inference	Angles Probability

Note: Each of the 18 subtests contained 4 questions each.
Inventory total, *N*=72

Questions on Cardiac Form and Function. To explore students' learning about the heart, participants were asked three times (i.e. pre-treatment, during treatment and post-treatment) when using zSpace®, “When you think about the structure and function of the human heart, what you like to know more about? Please list at least 1 question.” Student responses were recorded on paper, transcribed into Excel® and coded. A second science education researcher coded 120 of 453 student questions and interrater agreement was 95.3%. Responses were coded to capture themes of students’ learning and recoded with a second pass to capture salient features of the data (Creswell & Creswell, 2013), ensuring each student response was correctly categorized to the open codes established after the first pass. On a third round of coding, learning theory was applied to the statements using the active-constructive-interactive framework proposed by Chi (2009) to discern how the learning activities in zSpace® influenced students’ learning trajectories (active, constructive and interactive) of the heart over the course of the intervention. Active questions were defined in the framework as the lowest level of learning activity; underscored by questions where students activated existing knowledge, searched their existing knowledge, incorporated new information into or reorganized cognitive schemas. Active questions included student learning intentions, checks of prior knowledge, questions on heart form (appearance, terminology, shape, size, external features, composition, blood flow, blood volume), and heart function (general, heartbeat, and external structures). Constructive questions, the second level of learning activity, were categorized by student questions that indicated a restructuring of and repair of faulty knowledge or organization of personal knowledge beyond the scope of the presented instruction. Constructive questions included relating heart form to function, advanced functions of the heart (role of valves, regulation of heart rate, process of oxygenation), the role of the heart in overall health, and system relationships (heart-lung relationship, the heart as a complex, interconnected system, and the role of vessels as support agents to the heart). Interactive questions, the third and final level, included student questions indicating genuine interaction with the technology where new knowledge was generated from an expert's contributions (zSpace®). Interactive questions included questions beyond the scope of the content presented in the treatment, including heart homology and analogy to other species, aspects of heart malfunction (attack or infarction, failure, diseases or disorders, and arrhythmia), transplantation issues and methods of dissection and modeling. A two-way Analysis of Variance (ANOVA) was performed to explore interactions between student learning activities, grade level and time. A three-way ANOVA was used to determine interaction between prior cardiac knowledge (pre-test score) and student learning activity. Correlations using Spearman's rank correlation (rho) coefficients were made to determine relationships between student learning activities and IPDT tasks.

Limitations of the Study

Results of this study are limited to responses of participants who participated in zSpace® sessions and their retrospective reports about using the technology. The degree to which this sample is representative of perceptions of presence in 3-D HE VR is unknown. A limitation cited within existing presence research is the sole reliance on self-report (questionnaire) based measures to describe or generalize virtual presence (Slater 1999; Slater, 2004; Slater & Garau, 2007). Self-report measures, like the presence survey, have been shown to be effective in measuring user perceptions but not user responses to the virtual environment (Bailenson, Swinth, Hoyt, Persky, Dimov, & Blascovich, 2005, p.390). To address this and similar types of limitations, Azevedo (2015) recommends converging multiple sources of trace, product, and self-report data to cultivate an accurate model of learning (p.92). Product data (which may include knowledge construction if assessments are open-ended) are commonly used in education research via pre-tests and post-tests to evaluate student learning gains. This may provide strong evidence for cognitive ability provided there are assurances to construct validity and reliability (e.g. test, retest reliability, interrater reliability, and alternate forms).

CHAPTER 4: Results

Thirty-four analyses were conducted to explore significant differences, relationships, and interactions between study assessments. In the sections that follow the affordances of 3-D HE VR instruction for learning, comparison between 6th and 9th grade perceptions of presence, relationships between cognitive development and perceptions of presence, influence of 3-D HE VR instruction on conceptual understandings, and the relationship between prior knowledge and perceptions of presence are discussed. Table 5 describes the analyses and assessments related to each research question.

Table 5

Assessments and Analyses Related to Research Questions

	Assessments	Analyses
Research Question 1 Does a 3-D, haptic-enabled virtual reality technology experience promote understanding of cardiac anatomy and physiology for 6th and 9th grade students?	Test of Cardiac Knowledge	Paired T-Test (Table 6) Wilcoxin Signed Ranks Test (Tables 7, 8)
Research Question 2 How do 6th and 9th grade science students compare in their perceptions of presence when engaged in 3-D, haptic-enabled virtual reality instruction?	Presence Survey	Mann-Whitney U (Tables 9, 10, 11, 12)
Research Question 3 Is there a relationship between 6th and 9th grade students' cognitive dimensions and perceptions of presence?	Inventory of Piagetian Developmental Tasks (IPDT) Presence Survey	Spearman's Rho Correlation (Tables 13, 14, 15, 16, 17, 18)
Research Question 4 Does 3-D, haptic-enabled virtual reality technology influence learning for 6th and 9th grade students?	Student Questions Presence Survey IPDT	Frequency Count (Tables 19, 20) Framework Coding (Tables 21, 22)

Table 5 Continued

		ANOVA (Table 23) Spearman's Rho Correlation (Tables 24, 25, 26, 27, 28, 29, 30)
Research Question 5 Is there a relationship between 6th and 9th grade students' content knowledge and perceptions of presence?	Test of Cardiac Knowledge Presence Survey IPDT	ANOVA (Table 31) Spearman's Rho Correlation (Tables 32, 33, 34)

The analysis of the cardiac knowledge test for 6th and 9th grade students showed there were significant learning gains for both 6th and 9th grade (Table 6). For the 6th grade group, the pre-assessment mean was 30.17, (SD = 10.40) and the post assessment mean was 38.17 (SD = 15.62) with an alpha value of $p < 0.05$. Values for pre and post cardiac test scores for 9th grade were also significantly different (pre-assessment mean of 33.97 (SD = 12.85) and a post assessment mean of 49.90 (SD = 19.02)). These differences from pre to post instruction suggest the zSpace® system was effective in teaching students about cardiac anatomy and function at both grade levels.

Table 6

Results of 6th and 9th Grade Student Scores on a Test of Cardiac Knowledge

	Mean	Standard Deviation	Degrees of Freedom	Test Statistic	p-value
6th Grade					
Pre-test	30.17	10.40	74	-4.60	0.000*
Post-test	38.17	15.62			
9th Grade					
Pre-test	33.97	12.85	75	-8.90	0.000*
Post-test	49.90	19.02			

Note: Paired T-Test for 2 sample means: Alpha 2-tailed, * $p < 0.05$.

The open-ended cardiac drawing test, asked students to sketch and label the human heart from memory and the assessment was scored for five categories (heart shape, systems thinking, heart valves, heart vessels and heart chambers). The Wilcoxin signed ranked test showed there were significant learning gains for both 6th and 9th grade students (Table 7). The analysis showed that the zSpace® treatment resulted in differences in 6th grade that were statistically different for spatial understandings of heart shape (Z = -5.285, p = 0.000), systems thinking of the heart (Z = -5.145, p = 0.000), heart valves (Z = -4.610, p = 0.000), heart vessels (Z = -5.904, p = 0.000), and heart chambers (Z = -5.143, p = 0.000). There was a significant change in 9th grade students' spatial understandings of heart shape (Z = -3.161, p = 0.002), systems thinking of the heart (Z = -6.866, p = 0.000), heart valves (Z = -6.849, p = 0.000), heart vessels (Z = -6.454, p = 0.000), and heart chambers (Z = -6.446, p = 0.000).

Table 7

Results of 6th and 9th Grade Student Scores on an Open-ended Cardiac Drawing

Grade Level	6th Grade (*N*=75)		9th Grade (*N*=76)	
	Pre-test	Post-test	Pre-test	Post-test
Heart Shape				
Mean	1.88	2.71	2.37	2.88
Standard Deviation	1.20	0.83	1.18	0.85
Z Statistic		-5.285		-3.161
p-value		0.000**		0.002**
System Thinking about the Heart				
Mean	1.40	2.51	1.58	3.42
Standard Deviation	1.34	0.96	1.27	0.80
Z Statistic		-5.145		-6.866
p-value		0.000**		0.000**
Heart Valves				
Mean	0.840	1.65	0.750	2.78
Standard Deviation	0.855	1.27	0.676	1.29
Z Statistic		-4.610		-6.849
p-value		0.000**		0.000**
Heart Vessels				
Mean	0.880	1.80	0.895	2.30
Standard Deviation	0.569	1.03	0.579	1.21
Z Statistic		-5.904		-6.454

Table 7 Continued

p-value		0.000**		0.000**
Heart Chambers				
Mean	1.19	1.96	1.38	2.87
Standard Deviation	0.849	1.10	1.10	1.14
Z Statistic		-5.143		-6.446
p-value		0.000**		0.000**

Note: Wilcoxin Signed Ranked Test: Alpha 2-tailed, * $p < 0.05$, ** $p < 0.01$
The highest possible score per category is 4, the lowest a 0.

An assessment of open-ended assessment of cardiac circulation asked 6th and 9th grade students to trace the cardiac blood flow in three categories (circulation to the heart, within the heart and out of the heart). The Wilcoxin Signed Ranked Test showed there were significant learning gains for both 6th and 9th grade students for cardiac physiology and function (Table 8). For 6th grade students, there were no significant changes in their conceptual understanding of cardiac blood flow into the heart (Z = -1.017, p = 0.309) and blood flow out of the heart (Z = -1.708, p = 0.088). However, there was a significant change in conceptual understanding of blood flow inside the heart (Z = -2.381, p = 0.017). There were significant differences in pre and post assessment scores for 9th grade students for their conceptual understanding of cardiac blood flow into the heart (Z = -4.236, p = 0.000), blood flow inside the heart (Z = -3.915, p = 0.000), and blood flow out of the heart (Z = -4.272, p = 0.000).

Table 8

Results of 6th and 9th Grade Student Scores on an Open-ended Assessment of Cardiac Circulation

Grade Level	6th Grade (*N*=75)		9th Grade (*N*=76)	
	Pre-test	Post-test	Pre-test	Post-test
Cardiac Circulation Into the Heart				
Mean	0.80	0.95	1.12	1.80
Standard Deviation	0.96	1.09	0.91	1.35

Table 8 Continued

Z Statistic		-1.017		-4.236
p-value		0.309		0.000**
Cardiac Circulation Inside the Heart				
Mean	0.75	1.09	0.87	1.47
Standard Deviation	0.89	1.16	0.85	1.45
Z Statistic		-2.381		-3.915
p-value		0.017*		0.000**
Cardiac Circulation Out of the Heart				
Mean	0.52	0.72	0.93	1.61
Standard Deviation	0.74	0.97	0.82	1.34
Z Statistic		-1.708		-4.272
p-value		0.088		0.000**

Note: Wilcoxin Signed Ranked Test: Alpha 2-tailed, * $p < 0.05$, ** $p < 0.012$
The highest possible score per category is 4, the lowest a 0.

Tables 9, 10, 11 and 12 show the comparisons between 6th and 9th grade science students for perceptions of presence when engaged in 3-D, haptic-enabled virtual reality instruction. Using the Mann-Whitney U test to compare mean scores of perceived presence between 6th and 9th grade students, no significant differences were found for any items within the four presence constructs of control (Table 9), sensory (Table 10), distraction (Table 11), or realism (Table 12).

Table 9

Differences in 6th and 9th Grade Student Responses by Presence Control Construct

Presence Item	6th Grade Mean Rank	9th Grade Mean Rank	Mann Whitney U	*p* value
All Control Questions by Factor (Questions 1 through 21)	73.54	81.46	2659.50	0.270
1. I felt that I was in control of zSpace® 3-D environment during the session.	70.88	84.12	2454.50	0.041
2. zSpace® 3-D environment would respond to my actions.	69.78	85.22	2370.00	0.021
	78.64	76.36	2876.50	0.730

Table 9 Continued

3. zSpace® 3-D environment did what I wanted it to do.	75.54	79.46	2813.50	0.559
4. The interactions I had with the zSpace® 3-D environment were natural.	72.88	82.12	2609.00	0.162
5. I felt that the stylus allowed me to control what was occurring in the 3-D environment.	71.52	83.48	2504.00	0.079
6. The stylus would do what I wanted it to do in the 3-D environment.	74.27	80.73	2715.50	0.325
7. The interactions I had with the stylus to interact with the 3-D environment were natural.	70.78	84.22	2447.00	0.040
8. The stylus would respond to my actions when I interacted with the 3-D environment.	72.96	82.04	2615.00	0.162
9. The stylus allowed me to control the movement of objects in the environment.				
10. I was able to predict what would happen if I moved an object in the 3-D environment.	75.16	78.86	2784.50	0.581
11. I could move objects easily in the 3-D environment.	77.63	77.37	2954.50	0.969
12. I could manipulate objects easily in the 3-D environment.	78.48	76.52	2889.00	0.766
13. There was a delay between what I wanted to do and what happened on the screen.	70.77	84.23	2446.50	0.056
14. I adjusted quickly to the screen during the zSpace® session.	78.69	76.31	2872.50	0.725
15. I could easily move objects in the 3-D environment.	72.24	82.76	2559.50	0.110
16. I could easily interact with different objects in the 3-D environment.	74.40	80.60	2726.00	0.332
17. I could manipulate objects with a stylus in ways that I could not in the real world.	80.69	74.31	2718.50	0.336
18. I could easily zoom in on objects.	78.01	76.99	2925.00	0.881
19. I could easily zoom out from an object.	76.38	78.62	2878.00	0.744
20. I could navigate inside of objects using the stylus.	79.84	75.16	2784.00	0.487
21. I was able to navigate behind objects that I could not do normally in a 2-D simulation.	75.87	79.13	2839.00	0.614

Note: Mann-Whitney U: Differences in two independent groups, Alpha 2-tailed,
* $p < 0.002$.

There were no significant differences in presence scores between 6th and 9th grade students for all control constructs (Table 9).

Table 10

Differences in 6th and 9th Grade Student Responses by Presence Sensory Construct

Presence Item	6th Grade Mean Rank	9th Grade Mean Rank	Mann Whitney U	*p* value
All Sensory Questions by Factor (Questions 1 through 8)	79.29	75.71	2826.50	0.617
1. My sense of sight was highly engaged during the session.	79.16	75.84	2837.00	0.614
2. My sense of hearing was highly engaged during the session.	80.11	74.89	2763.50	0.443
3. My sense of touch was highly engaged during the session.	82.36	72.64	2590.00	0.159
4. I was convinced that the objects I viewed with zSpace® were moving through space.	75.62	79.38	2820.00	0.589
5. I was able to explore all of the 3-D environment with my sight.	77.27	77.73	2947.00	0.945
6. I was able to explore all of the 3-D environment with my sense of touch.	78.97	76.03	2851.00	0.675
7. I was able to closely examine objects during the zSpace® session.	76.58	78.42	2893.50	0.777
8. I was able to closely examine objects from multiple viewpoints during the zSpace® session.	76.20	78.80	2864.50	0.687

Note: Mann-Whitney U: Differences in two independent groups, Alpha 2-tailed, * $p < 0.006$.

There were no significant differences in presence scores between 6th grade and 9th grade students for all sensory constructs (Table 10).

Table 11

Differences in 6th and 9th Grade Student Responses by Presence Distraction Construct

Presence Item	6th Grade Mean Rank	9th Grade Mean Rank	Mann Whitney U	*p* value
All Distraction Questions by Factor (Questions 1 through 17)	79.35	75.65	2822.00	0.606
1. I was aware of other events in the classroom during the zSpace® session.	75.82	79.18	2835.50	0.631
2. I was aware of sounds outside of the zSpace® session.	71.88	83.12	2532.00	0.108
3. I was aware of the stylus I used to control objects in zSpace®.	77.14	77.86	2937.00	0.914
4. I was aware of the 3-D glasses I used to view objects in zSpace®.	78.92	76.08	2855.00	0.679
5. I was aware of the zSpace® monitor I used to view objects in zSpace®.	78.21	76.79	2909.50	0.834
6. I was aware of the zSpace® camera during the session.	81.75	73.25	2637.00	0.220
7. I was very involved during the zSpace® session.	81.48	73.52	2658.00	0.217
8. The 3-D glasses were distracting.				
9. The stylus was distracting.	81.73	73.27	2638.50	0.222
10. The 3-D objects in the environment were	81.34	73.66	2668.50	0.262
distracting.	77.89	77.11	2934.50	0.909
11. Other students were distracting me during the zSpace® session.	84.04	70.96	2461.00	0.047
12. The stylus interfered when I moved objects in the 3-D environment.	73.72	81.28	2673.50	0.284
13. The glasses interfered when I moved objects in the 3-D environment.	73.94	81.06	2690.00	0.304
14. I was able to concentrate easily during the zSpace® session.	83.66	71.34	2490.50	0.066
15. I was comfortable using the stylus during the zSpace® session.	82.18	72.82	2604.00	0.164
16. I was comfortable using the 3-D glasses during the zSpace® session.	81.52	73.48	2655.00	0.229
17. I felt comfortable viewing the objects in the 3-D environment.	80.27	74.73	2751.00	0.407

Note: Mann-Whitney U: Differences in two independent groups, Alpha 2-tailed, * $p < 0.003$.

There were no significant differences in presence scores between 6th grade and 9th grade students for all distraction constructs (Table 11).

Table 12

Differences in 6th and 9th Grade Student Responses by Presence Realism Construct

Presence Item	6th Grade Mean Rank	9th Grade Mean Rank	Mann Whitney U	*p* value
All Realism Questions by Factor (Questions 1 through 15)	78.39	76.61	2896.00	0.804
1. The zSpace®® 3-D objects were not realistic.	78.43	76.57	2893.00	0.787
2. I felt disconnected during the zSpace®® session.	78.78	76.22	2866.00	0.706
3. My experiences during the zSpace®® session were similar to real laboratory experiences.	78.98	76.02	2850.50	0.674
4. The 3-D environment was realistic.	81.57	73.43	2651.00	0.239
5. I felt disoriented when I put the stylus down.	75.37	79.63	2800.50	0.544
6. I felt confused when I put the stylus down.	78.73	76.27	2870.00	0.722
7. I felt disoriented when I removed the 3-D glasses.	77.68	77.32	2951.00	0.960
8. I felt confused when I removed the 3-D glasses.	78.96	76.04	2852.00	0.674
9. I lost track of time during the zSpace® session.	79.90	75.10	2780.00	0.496
10. I could transition from the real world to using zSpace® easily.	78.47	76.53	2890.00	0.778
11. The illusion of the 3-D environment was very real to me.	77.91	77.09	2933.00	0.904
12. The object appeared to jump out of the screen.	74.72	80.28	2750.50	0.411
13. Using zSpace® to view objects is more realistic than using a simulation on a / computer.	72.32	82.68	2565.50	0.112
14. Using zSpace® to view objects is more realistic than watching a video.	74.56	80.44	2738.00	0.375
15. Using zSpace® to view objects is more realistic / that participating in lab at school.	80.64	74.36	2722.50	0.368

Note: Mann-Whitney U: Differences in two independent groups, Alpha 2-tailed, * $p < 0.003$.

There were no significant differences in presence scores between 6th grade and 9th grade students for all realism constructs (Table 12).

To explore relationships between students' cognitive dimensions in Piagetian development and perceptions of presence, a Spearman's correlation was performed with a p-value of 0.05 between the IPDT constructs: Laws (Table 13), Relations (Table 14), Conservation (Table 15), Images (Table 16), and Classification (Table 17) with the four constructs of presence (Control, Sensory, Distraction and Realism). Table 13 shows the correlations between the students' performance on the IPDT inventory for Laws (which includes questions on rotation, angles and probability) and presence. The Laws and Control variables for 6th grade were significantly correlated, $r = .260$, $p < .05$, as well as the subtests of rotation to control $r = .293$, $p < .01$, and angles $r = .229$, $p < .05$. There is also a significant negative correlation between the Laws variable and distraction for 6th grade

$r = -.249$, $p < .05$. There were only nonsignificant correlations for the constructs of sensory and realism for 6th grade and no construct was significant for the 9th grade.

Table 13

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Laws and Presence Constructs

	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (N=75)				
Laws (N=12)	0.260*	0.095	-0.249*	0.073
Rotation (N=4)	0.293**	0.217	-0.144	0.073
Angles (N=4)	0.229*	0.042	-0.208	-0.065
Probability (N=4)	0.147	0.037	-0.176	0.131
9th Grade (N=76)				
Laws (N=12)	-0.110	-0.132	0.048	-0.072
Rotation (N=4)	-0.055	-0.076	-0.016	-0.120
Angles (N=4)	-0.073	-0.033	0.020	-0.001
Probability (N=4)	-0.061	-0.158	-0.007	-0.022

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.

Values range from 0 to 1.

* $p < 0.05$; ** $p < 0.01$ (Bonferroni correction)

Correlations between the students' performance on the IPDT inventory for Relations (which includes questions on sequence, seriation, and inference) and presence are shown in Table 14. The Relations and Sensory variables for 9th grade were significantly correlated, r = -0.276, $p < .01$. There were nonsignificant correlations for all remaining constructs within Relations for both 6th and 9th grade students.

Table 14

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Relations and Presence Constructs

	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (*N*=75)				
Relations (*N*=12)	0.087	0.058	-0.072	0.067
Sequence (*N*=4)	0.020	-0.002	-0.084	0.035
Seriation (*N*=4)	0.058	0.029	-0.223	-0.045
Inference (*N*=4)	0.191	0.134	0.063	0.148
9th Grade (*N*=76)				
Relations (*N*=12)	-0.049	-0.276**	-0.128	0.017
Sequence (*N*=4)	-0.013	-0.063	-0.116	-0.005
Seriation (*N*=4)	-0.051	-0.220	-0.027	-0.084
Inference (*N*=4)	-0.052	-0.128	-0.046	0.133

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.01$ (Bonferroni correction)

Correlations between the students' performance on the IPDT inventory for Conservation (which includes questions on quantity, weight, volume and distance) and presence are shown in Table 15. The weight and sensory variables for 6th grade were significantly correlated, $r = -0.244$, $p < .05$. There were nonsignificant correlations for the remaining constructs of conservation for 6th and 9th grade.

Table 15

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Conservation and Presence Constructs

	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (*N*=75)				
Conservation (*N*=16)	0.184	-0.116	-0.034	-0.008
Quantity (*N*=4)	0.140	0.016	0.106	0.039
Weight (*N*=4)	0.039	-0.244*	-0.160	-0.037
Volume (*N*=4)	0.171	0.075	0.016	0.050
Distance (*N*=4)	0.042	-0.056	-0.022	-0.066
9th Grade (*N*=76)				
Conservation (*N*=16)	-0.126	-0.154	0.111	0.016
Quantity (*N*=4)	-0.129	-0.132	0.154	0.020
Weight (*N*=4)	0.051	0.106	0.069	0.133
Volume (*N*=4)	-0.163	-0.131	0.002	-0.037
Distance (*N*=4)	-0.002	-0.098	0.129	-0.062

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$

Table 16 shows correlations between the students' performance on the IPDT inventory for Images (which includes questions on levels, perspective, movement and shadows). Correlations were non-significant for the constructs of images and presence for 6th and 9th grade.

Table 16

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Images and Presence Constructs

	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (*N*=75)				
Images (*N*=16)	0.140	-0.035	-0.153	-0.046
Levels (*N*=4)	0.151	0.042	-0.179	-0.051
Perspective (*N*=4)	0.149	0.076	-0.033	0.060
Movement (*N*=4)	-0.027	-0.094	0.024	0.069
Shadows (*N*=4)	0.085	-0.121	-0.198	-0.083
9th Grade (*N*=76)				
Images (*N*=16)	-0.105	-0.092	0.022	-0.035

Table 16 Continued

Levels (*N*=4)	-0.070	0.121	0.079	-0.045
Perspective (*N*=4)	-0.005	-0.035	0.013	-0.077
Movement (*N*=4)	-0.159	-0.177	-0.002	0.048
Shadows (*N*=4)	-0.029	-0.087	0.098	-0.097

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$

Correlations between the students' performance on the IPDT inventory for Classification (e.g, matrix, symbols, classes and inclusion) and presence are shown in Table 17. The matrix and control variables for 6th grade were significantly correlated, r = -0.244, $p < .05$. For 9th grade, inclusion and sensory variables were negatively correlated, r = -0.237, $p < .05$. There were nonsignificant correlations for remaining constructs of classification for 6th and 9th grade.

Table 17

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Classification and Presence Constructs

	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (*N*=75)				
Classification (*N*=16)	0.212	0.032	-0.016	-0.007
Matrix (*N*=4)	0.244*	0.081	-0.082	-0.189
Symbols (*N*=4)	0.091	-0.065	0.028	0.115
Classes (*N*=4)	-0.046	-0.048	-0.147	0.046
Inclusion (*N*=4)	0.227	0.046	0.091	0.021
9th Grade (*N*=76)				
Classification (*N*=16)	0.008	-0.016	0.068	0.018
Matrix (*N*=4)	0.043	0.104	-0.164	0.051
Symbols (*N*=4)	-0.036	0.111	0.053	-0.101
Classes (*N*=4)	0.008	-0.014	0.134	0.066
Inclusion (*N*=4)	-0.051	-0.237*	-0.042	0.051

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$

IPDT constructs were organized according to cognitive difficulty and related age ranges as validated by Patterson and Milakofsky (1980). Low range questions, of which 7 to 8 year old children typically score correctly contain questions of matrix, symbols, movement, quantity, sequence and serration. Midrange questions, of which 9 to 10 year old children typically score correctly contain questions of levels, perspective, shadows, weight, distance, and rotation. High range questions, of which 11 to 13 year old children typically score correctly contain questions of classes, inclusion, volume, inference, angles and probability. (See Table 4 for IPDT subtests by difficulty and construct.) Table 18 shows the correlations between the students' performance on the IPDT inventory for cognitive classification (which includes questions on low range, midrange, and high range) and presence constructs. For 6th grade students, high range questions and control were significantly correlated, $r = .255$, $p < .02$, as well as midrange questions to distraction $r = -.281$, $p < .02$. There were only nonsignificant correlations for the constructs of cognitive classification and presence for 9th grade students. These results suggest younger students (6th grade) with a strong conceptual understanding of the aspects (e.g. volume, angles) that contribute to virtual environments, reported more control of the 3-D HE VR environment in their presence survey. Whereas students who had less of an understanding of aspects (e.g. distance, perspective, rotation) that contribute to virtual environments reported more distraction within the 3-D HE VR space.

Table 18

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Cognitive Classifications (proficiency by age) and Presence Constructs

Measure	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (*N*=75)				
Low Range (7-8)	0.106	-0.029	-0.057	-0.027
Midrange (9-10)	0.192	-0.071	-0.281**	-0.062
High Range (11-13)	0.255**	0.070	-0.106	0.094
9th Grade (*N*=76)				
Low Range (7-8)	-0.137	-0.155	-0.037	-0.062
Midrange (9-10)	-0.057	-0.066	0.085	-0.083
High Range (11-13)	-0.123	-0.191	0.066	0.014

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.02$ (Bonferroni correction)

As described earlier, to determine Students' conceptual understandings were open coded for cardiac form (appearance, terminology, shape, size, external features, composition, blood flow, blood volume), function (general, beating, external structures), connection between form and function, role in health, relationships, (other body systems, arteries and veins), analogy (other species), as a system (within the heart and to the lungs), advanced functioning (valves, heart rate, role in gas exchange), heart malfunctioning (attack/infarction, failure, disorder/disease, arrhythmia), transplantation and modeling for dissection (Tables 19 and 20).

Table 19

Frequencies of Types of Questions Asked Prior, During, and After Treatment about the Human Heart (6th Grade)

Category	Prior to Treatment (*N* = 119)	During Treatment (*N* = 78)	After Treatment (*N* = 86)	Student Example
Student Learning Intention	0	3	2	*I want to learn more on how the heart systems work.*

Table 19 Continued

Check of Prior Knowledge	22	0	0	*I would like to know how it connects with the circulatory system.*
Form (Appearance, Terminology, Shape, Size, External Features, Composition, Blood Flow, Blood Volume)	43	14	13	*What does a heart look like?*
Function (General Heart Function, Heart Beat, External Features)	41	7	6	*How does the heart use the blood?*
Relationship of Form to Function	6	11	5	*Why is it the size of your fist?*
Advanced Function (Valves, Heart Rate, Oxygenation)	0	16	28	*How do the valves close and open?*
Cardiac Role in overall Health	3	5	6	*How it is so important to the body?*
Relationships as a System (Lungs, Heart, Vessels)	4	14	15	*How does the heart correlate with the lungs to function properly?*
Homology/ Analogy to other Species	0	1	0	*How many hearts do octopi have and how large it is compared to ours?*

Table 19 Continued

Cardiac Malfunction (Attack/ Infarction, Failure, Disease/Disorder, Arrhythmia)	0	6	7	*What does the heart look like during a heart attack?*
Transplantation	0	0	2	*If someone needs a new heart why does the heart have to be the same as the heart the person who had the heart attack?*
Cardiac Modeling and Dissection	0	1	2	*How you would you dissect the heart?*

Note: Some student responses included more than 1 question which was coded in the appropriate category.

Table 20

Frequencies of Types of Questions Asked Prior, During, and After Treatment about the Human Heart (9th Grade)

Category	Prior to Treatment (*N* = 120)	During Treatment (*N* = 91)	After Treatment (*N* = 95)	Student Example
Student Learning Intention	0	2	4	*What is a better/easier way to understand the heart and learn it?*
Check of Prior Knowledge	19	0	0	*Why does the heart look different than we draw it? Like this* ♡
Form (Appearance, Terminology, Shape, Size, External Feat., Composition, Blood Flow, Blood Volume)	51	14	11	*How does a heart feel?*

Table 20 Continued

Function (General Heart Function, Heart Beat, External Feat.)	30	2	3	*What makes it beat?*
Relationship of Form to Function	5	8	10	*Why does the heart have so many chambers?*
Advanced Function (Valves, Heart Rate, Oxygenation)	5	24	23	*Is one side of the heart larger than another?*
Cardiac Role in overall Health	3	6	3	*How do I make sure my heart is healthy?*
Relationships as a System (Lungs, Heart, Vessels)	3	18	23	*What is each part's role in the heart?*
Homology/ Analogy to other Species	1	2	2	*What would happen if a human and another organism switched hearts?*
Cardiac Malfunction (Attack/ Infarction, Failure, Disease/Disorder, Arrhythmia)	3	15	14	*What would happen if the heart is not getting enough oxygen?*
Transplantation	0	0	0	----
Cardiac Modeling and Dissection	0	0	2	*I would like to see different types of hearts such as unhealthy ones and see how much they differ from healthy ones.*

Note: Some student responses included more than 1 question which was coded in the appropriate category.

The analyses of the questions asked by students showed 6th grade students asked 151 active learning questions, 106 prior to treatment, 24 during treatment and 21 after treatment (Table 21). Active questioning comprised 53.3% of all questions asked by the 6th grade sample. Sixth grade students asked 113 constructive learning questions, (13 prior to treatment, 46 during treatment and 54 after treatment). Constructive questioning made up 40.0% of the total questions asked by the 6th grade sample. Sixth grade students asked 19 interactive learning questions, (0 prior to treatment, 8 during treatment and 11 after treatment). Interactive questioning was 7.0% of the total questions asked by the 6th grade sample.

Table 21

Coded Questions using Chi's Active-Constructive-Interactive Framework (6th Grade)

Category	Prior to Treatment	During Treatment	After Treatment	Open Code Categories
Responses (*N* = 283)				
Active	106	24	21	Student Learning Intention Check of Prior Knowledge, Form (Appearance, Terminology, Shape, Size, External Features, Composition, Blood Flow, Blood Volume) Function (General, Heart Beat, External Structures)
Constructive	13	46	54	Form to Function Advanced Function (Valves, Heart Rate, Oxygenation) Cardiac Role in overall Health Relationship as a System (Lungs, Heart, Vessels)

Table 21 Continued

Interactive	0	8	11	Homology/Analogy to other Species Heart Malfunction (Attack/Infarction, Failure, Disease/Disorder, Arrhythmia) Transplantation Dissection/Modeling

Note: Each student was asked to record at least one question per time period (prior to treatment, during treatment and after treatment).

Ninth grade students asked 136 active learning questions, (100 prior to treatment, 18 during treatment and 18 after treatment). Active questioning was 44.4% of all questions asked by the 9th grade sample. Ninth grade students asked 131 constructive learning questions, (16 prior to treatment, 56 during treatment and 59 after treatment). Constructive questioning was 43.0% of all questions asked by the 9th grade sample. Ninth grade students asked 39 interactive learning questions, (4 prior to treatment, 17 during treatment and 18 after treatment). Interactive questioning was 12.7% of the all questions asked by the 9th grade sample.

Table 22

Coded Questions using Chi's Active-Constructive-Interactive Framework (9th Grade)

Category	Prior to Treatment	During Treatment	After Treatment	Open Code Categories
Responses (*N* = 306)				
Active	100	18	18	Student Learning Intention Check of Prior Knowledge, Form (Appearance, Terminology, Shape, Size, External Features, Composition, Blood Flow, Blood Volume) Function (General, Heart Beat, External Structures)

Table 22 Continued

Constructive	16	56	59	Form to Function Advanced Function (Valves, Heart Rate, Oxygenation) Cardiac Role in overall Health Relationship as a System (Lungs, Heart, Vessels)
Interactive	4	17	18	Homology/Analogy to other Species Heart Malfunction (Attack/Infarction, Failure, Disease/Disorder, Arrhythmia) Transplantation Dissection/Modeling

Note: Each student was asked to record at least one question per time period (prior to treatment, during treatment and after treatment).

To explore interactions between the categories of student questions by time period (prior, during and after instruction) and grade level, a two-way analysis of variance (ANOVA) was completed. Table 23 shows there was a significant main effect of active learning activities (questions) per time period, $F = 21.48$, $p < .05$, constructive learning activities (questions) per time period, $F = 8.702$, $p < .05$, and interactive learning activities (questions) per time period, $F = 4.951$, $p < .05$. There were no significant interactions for grade level learning activities (questions) between 6th and 9th grade or any significant interactions between grade levels and time. Figure 6 shows the interaction for active, constructive and interactive questioning by time period and grade level, respectively.

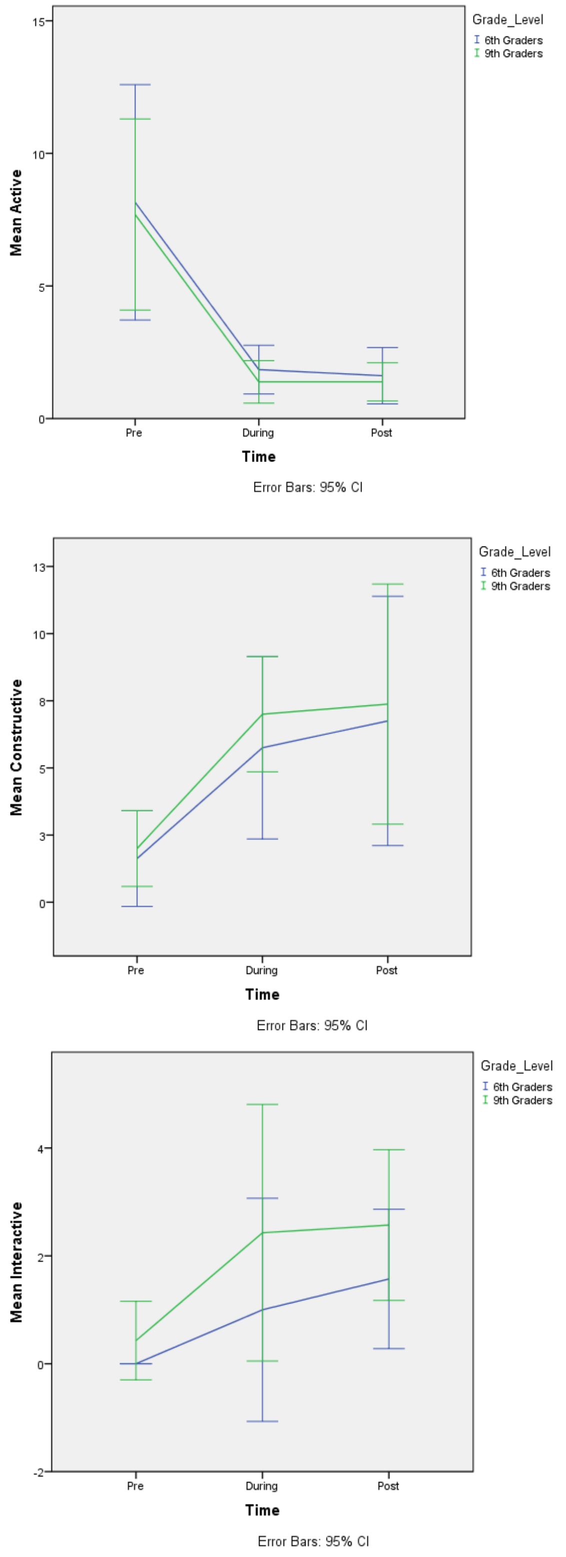
Table 23

Two-way Analysis of Variance (ANOVA) Between Student Questioning by Time and Grade Level (6th and 9th Grade)

	df	*SS*	*MS*	*F*	*P*
Active					
Grade Level	1	2.885	2.885	0.176	0.676
Time	2	702.5	351.2	21.48	0.000*
Grade Level*Time	2	0.231	0.115	0.007	0.993
Constructive					
Grade Level	1	6.750	6.750	0.451	0.506
Time	2	260.5	130.3	8.702	0.001*
Grade Level*Time	2	1.625	0.812	0.054	0.947
Interactive					
Grade Level	1	9.524	9.524	3.468	0.071
Time	2	27.19	13.60	4.951	0.013*
Grade Level*Time	2	1.762	0.881	0.321	0.728

Note: * indicates significance at the $p < 0.05$ level.

Figure 6. ANOVA outputs for active, constructive, and interactive questions per time period and grade level.



Error Bars: 95% CI

Error Bars: 95% CI

Error Bars: 95% CI

Correlations between student questioning (active, constructive, and interactive) and students' perceptions of presence are shown in Table 24. Constructive questions and distraction variables for 6th grade were significantly correlated, $r = -0.285$, $p < .01$. There were nonsignificant correlations for the remaining student questioning categories and perceptions of presence for 6th and 9th grade.

Table 24

Correlations Between Student Questioning and Presence Constructs

	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (*N*=75)				
Active	-0.061	-0.193	0.116	-0.135
Constructive	0.103	0.075	-0.285**	0.095
Interactive	-0.135	-0.107	0.043	-0.124
9th Grade (*N*=76)				
Active	-0.021	-0.094	-0.069	0.066
Constructive	0.168	0.088	0.146	-0.007
Interactive	-0.007	-0.044	-0.073	-0.064

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.01$ (Bonferroni correction)

Correlations between IPDT scores on the construct of laws and student questioning (active, constructive, and interactive) is shown in Table 25. Rotation and constructive questioning for 6th grade were significantly correlated, $r = -0.269$, $p < .05$. Probability and interactive questioning for 9th grade were significantly correlated, $r = 0.327$, $p < .01$. There were nonsignificant correlations for the remaining student questioning and IPDT proficiency scores in laws for 6th and 9th grade.

Table 25

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Laws and Student Questioning

	Active	Constructive	Interactive
6th Grade (*N*=75)			
Laws (*N*=12)	-0.131	0.014	0.024
Rotation (*N*=4)	0.211	-0.269*	0.082
Angles (*N*=4)	-0.027	-0.185	0.032
Probability (*N*=4)	-0.014	-0.114	0.058
9th Grade (*N*=76)			
Laws (*N*=12)	-0.126	-0.023	0.139
Rotation (*N*=4)	0.181	-0.130	0.177
Angles (*N*=4)	0.037	0.046	0.023
Probability (*N*=4)	0.009	-0.105	0.327**

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.01$ (Bonferroni correction)

Correlations between IPDT scores on the construct of relations and student questioning (active, constructive, and interactive) is shown in Table 26. In 6th grade, sequence and active questioning variables were significantly correlated $r = -0.243$, $p < .05$ as well as sequence and interactive questioning were significantly correlated, $r = 0.238$, $p < .05$. Relations and active questioning for 9th grade were significantly correlated, $r = -0.219$, $p < .01$. Sequence and constructive questioning for 9th grade were significantly correlated, $r = -0.219$, $p < .05$. There were nonsignificant correlations for the remaining student questions and IPDT proficiency scores in relations for 6th and 9th grade.

Table 26

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Relations and Student Questioning

	Active	Constructive	Interactive
6th Grade (*N*=75)			
Relations (*N*=12)	0.185	-0.043	0.046
Sequence (*N*=4)	-0.243*	-0.020	0.238*
Seriation (*N*=4)	0.097	-0.044	0.075
Inference (*N*=4)	-0.038	-0.070	-0.097
9th Grade (*N*=76)			
Relations (*N*=12)	-0.219*	-0.001	0.049
Sequence (*N*=4)	0.094	-0.219*	0.042
Seriation (*N*=4)	0.063	-0.156	0.225
Inference (*N*=4)	-0.014	0.189	0.059

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$

Correlations between IPDT scores on the construct of conservation and student learning activities (active, constructive, and interactive) in Table 27. In 9th grade, three IPDT interactive learning variables were significantly correlated, quantity, $r = 0.228$, $p < .05$, weight, $r = 0.336$, $p < .01$, and volume, $r = 0.267$, $p < .05$. There were nonsignificant correlations for the remaining student learning activities and IPDT proficiency scores in conservation for 6th and 9th grade.

Table 27

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Conservation and Student Questioning

	Active	Constructive	Interactive
6th Grade (*N*=75)			
Conservation (*N*=16)	0.123	-0.146	0.162
Quantity (*N*=4)	-0.078	-0.110	0.093
Weight (*N*=4)	-0.063	-0.030	-0.106
Volume (*N*=4)	-0.023	0.008	-0.021
Distance (*N*=4)	0.038	-0.104	0.159

Table 27 Continued

9th Grade (*N*=76)			
Conservation (*N*=16)	-0.031	0.020	-0.132
Quantity (*N*=4)	0.101	-0.033	0.228*
Weight (*N*=4)	0.053	-0.132	0.336**
Volume (*N*=4)	0.201	-0.125	0.267*
Distance (*N*=4)	0.110	-0.060	0.178

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.01$ (Bonferroni correction)

Correlations between IPDT scores on the construct of images and questioning (active, constructive, and interactive) in Table 28. Correlations were non-significant for the constructs of images and student questioning for 6th and 9th grade.

Table 28

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Images and Student Questioning

	Active	Constructive	Interactive
6th Grade (*N*=75)			
Images (*N*=16)	0.052	-0.029	0.161
Levels (*N*=4)	-0.190	-0.167	-0.014
Perspective (*N*=4)	0.052	0.014	-0.157
Movement (*N*=4)	0.049	-0.006	0.071
Shadows (*N*=4)	-0.154	0.157	0.025
9th Grade (*N*=76)			
Images (*N*=16)	-0.091	-0.009	-0.044
Levels (*N*=4)	-0.041	-0.085	0.121
Perspective (*N*=4)	0.034	0.074	0.044
Movement (*N*=4)	0.128	0.171	-0.027
Shadows (*N*=4)	-0.006	0.117	0.054

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$

Correlations between IPDT scores on the construct of classification and student learning activities (active, constructive, and interactive) are shown in Table 29. Correlations were non-significant for the constructs of classification and student questioning for 6th and 9th grade.

Table 29

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Construct of Classification and Student Questioning

	Active	Constructive	Interactive
6th Grade (*N*=75)			
Classification (*N*=16)	0.015	0.018	0.134
Matrix (*N*=4)	-0.164	0.105	-0.186
Symbols (*N*=4)	-0.016	-0.194	0.065
Classes (*N*=4)	-0.026	-0.053	-0.007
Inclusion (*N*=4)	0.006	-0.025	0.105
9th Grade (*N*=76)			
Classification (*N*=16)	-0.022	-0.114	0.098
Matrix (*N*=4)	0.045	0.023	0.083
Symbols (*N*=4)	0.173	-0.055	0.145
Classes (*N*=4)	0.037	0.112	0.015
Inclusion (*N*=4)	0.138	0.047	0.178

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$

Correlations between IPDT scores on cognitive classification (low range, midrange, and high range) and student questioning (active, constructive, and interactive) are shown in Table 30. In 9th grade, midrange questions and interactive learning variables were significantly correlated, $r = 0.292$, $p < .02$, as well as high range questions and interactive learning variables, $r = 0.261$, $p < .05$. There were nonsignificant correlations for IPDT cognitive classification and student learning activities for the remaining variables for 6th and 9th grade students. This suggests adolescent students who score better in questions of spatial understanding ask more interactive level questioning, going beyond the stated curriculum to construct new knowledge.

Table 30

Correlations Between Inventory of Piaget's Developmental Tasks (IPDT) Cognitive Classifications (proficiency by age) and Student Questioning

	Active	Constructive	Interactive
6th Grade (*N*=75)			
Low Range (7-8)	0.209	-0.089	0.121
Midrange (9-10)	0.018	-0.022	0.171
High Range (11-13)	-0.028	-0.021	0.074
9th Grade (*N*=76)			
Low Range (7-8)	0.197	-0.050	0.201
Midrange (9-10)	0.151	-0.126	0.292**
High Range (11-13)	0.137	0.012	0.261*

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.02$ (Bonferroni correction)

To explore interactions between students' prior knowledge of the heart (pre-test score on a standardized cardiac assessment) and the categories of student questioning by time period (prior, during and after instruction), a three-way analysis of variance (ANOVA) was completed. There was a statistically significant interaction with 6th grade students' pre-test scores and student questioning, $F = 7.406$, $p = 0.043$ and a significant two-way interaction with 6th grade active and interactive questioning, $F = 6.769$, $p = 0.012$ shown in Table 31. There were no significant interactions for 9th grade students between pre-test score and their questioning level.

Table 31

Three-way Analysis of Variance (ANOVA) of Students' Pre-test Scores on a Standardized Cardiac Assessment by Student Questioning (Active, Constructive and Interactive)

	df	*SS*	*MS*	*F*	*P*
6th Grade					
Active	3	885.6	295.2	2.897	0.043*
Constructive	4	281.0	70.3	0.689	0.602
Interactive	2	146.8	73.4	0.720	0.491
Active*Constructive	5	570.0	114.0	1.119	0.361
Active*Interactive	1	689.7	689.7	6.769	0.012*
Constructive*Interactive	2	253.7	126.8	1.245	0.296

Table 31 Continued

Active*Constructive*Interactive	0	0.000	---	---	---
9th Grade					
Active	4	1166.0	291.6	1.903	0.126
Constructive	4	899.7	224.9	1.468	0.227
Interactive	3	450.8	150.3	0.980	0.410
Active*Constructive	5	810.8	162.2	1.058	0.396
Active*Interactive	3	415.8	138.6	0.904	0.446
Constructive*Interactive	4	259.1	64.8	0.423	0.791
Active*Constructive*Interactive	1	468.5	468.5	3.057	0.087

Note: * indicates significance at the $p < 0.05$ level.

For 9th grade students, pre-test scores on a test of cardiac knowledge were significantly correlated to sensory presence scores, $r = -0.255$, $p < .05$, shown in Table 32. A the three-way interaction between active, constructive and interactive questioning for 6th grade students was incalculable due to the absence of interactive questions prior to instruction resulting in zero degrees of freedom. The remaining correlations for 6th and 9th grade between their pre-test scores and presence were nonsignificant.

Table 32

Correlations Between Students' Scores on a Test of Cardiac Knowledge and Presence Constructs

	1 (Control)	2 (Sensory)	3 (Distraction)	4 (Realism)
6th Grade (*N*=75)				
Pre-Test	0.018	-0.091	0.148	-0.122
Post-Test	0.121	0.007	-0.256*	-0.126
Gain Score	0.074	-0.018	-0.356***	-0.078
9th Grade (*N*=76)				
Pre-Test	-0.077	-0.255*	-0.046	-0.109
Post-Test	-0.075	-0.165	0.054	-0.023
Gain Score	-0.009	0.006	0.073	0.073

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.01$ (Bonferroni correction), *** $p < 0.001$

Correlations between pre-test scores on a test of cardiac knowledge and students' Inventory of Piaget's Developmental Tasks (IPDT) subset scores (classification, images, conservation, relations and laws) are shown in Table 33. In 9th grade students, pre-test scores were significantly correlated for classification, $r = 0.421$, $p < .001$, images, $r = 0.292$, $p < .01$, conservation, $r = 0.392$, $p < .001$, relations, $r = 0.249$, $p < .05$, and laws, $r = 0.441$, $p < .001$. One significant correlation between pre-test scores and conservation questions, $r = 0.227$, $p < .05$ was found for 6th grade students. The remaining correlations for 6th grade students between their pre-test scores and IPDT subsets were nonsignificant.

Table 33

Correlations Between Student Test Scores on a Test of Cardiac Knowledge and Subset Scores on the Inventory of Piaget's Developmental Tasks (IPDT)

	Classification (*N*=16)	Images (*N*=16)	Conservation (*N*=16)	Relations (*N*=12)	Laws (*N*=12)
6th Grade (*N*=75)					
Pre-Test Score	0.115	0.078	0.227*	0.034	-0.038
Post-Test Score	0.516***	0.380***	0.279**	0.311**	0.367***
Gain Score	0.447***	0.334**	0.139	0.254*	0.398***
9th Grade (*N*=76)					
Pre-Test Score	0.421***	0.292**	0.392***	0.249*	0.441***
Post-Test Score	0.570***	0.358**	0.447***	0.310**	0.334**
Gain Score	0.348**	0.224	0.249*	0.189	0.065

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients. Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.01$ (Bonferroni correction), *** $p < 0.001$

Correlations between pre-test scores on a test of cardiac knowledge and cognitive classification (low range, midrange, and high range) are shown in Table 34. For 9th grade students, pre-test scores were significantly correlated to low range, $r = 0.442$, $p < .001$, midrange, $r = 0.401$, $p < .001$, and high range questions, $r = 0.465$, $p < .001$. There were nonsignificant correlations for the remaining pre-test scores and IPDT cognitive classifications for 6th grade students.

Table 34

Correlations Between Student Test Scores on a Test of Cardiac Knowledge and Inventory of Piaget's Developmental Tasks (IPDT) Cognitive Classifications (proficiency by age)

	Low Range (7-8)	Midrange (9-10)	High Range (11-13)
6th Grade (*N*=75)			
Pre-Test Score	0.041	0.157	0.058
Post-Test Score	0.435***	0.412***	0.498***
Gain Score	0.394***	0.304**	0.466***
9th Grade (*N*=76)			
Pre-Test Score	0.442***	0.401***	0.465***
Post-Test Score	0.578***	0.367***	0.525***
Gain Score	0.332**	0.155	0.288**

Note: Correlations with these variables are Spearman's rank correlation (rho) coefficients.
Values range from 0 to 1.
* $p < 0.05$; ** $p < 0.02$ (Bonferroni correction), *** $p < 0.001$

CHAPTER 5: Discussion and Conclusion

Discussion of Results

In this study, relationships were explored between students' cognitive abilities, understanding of cardiac content, and perceptions of presence while engaged in a 3-D HE VR experience on the human heart. In relation to student learning, both 6th and 9th grade students had significant learning gains on the test of cardiac knowledge. Students' drawings and labels of the heart showed growth from pre to post treatment for each of the five scored categories (i.e. shape, system thinking, valves, vessels and chambers). When students were tasked with tracing cardiac blood flow into, through and out of the heart, 9th grade participants showed significant gains in in all three categories, whereas 6th grade gains were solely in internal cardiac circulation. Because 6th grade students did not show improvement in these other two categories, it may be due to a common misconception regarding circulation to and from the heart due the role of oxygen exchange (Allen, 2010, p.44). Although circulation into and out of the heart was discussed within the module (Appendix D), students only virtually dissected the main body of the heart to explore internal circulation. Dwyer (1978) described this as a limitation of cardiac visualization, where people generally remember less of what they hear than what they see and directly engage with, respectively. This may be particularly true for younger learners whose primary mode of acquiring knowledge tends to be through direct action (Wadsworth, 1996) and sensory processing is predominantly visual (Schmid, Büchel, & Rose, 2011). Due to significant growth in almost all categories for both groups, this suggests that 3-D HE VR science instruction may serve as a powerful instructional tool for middle grade and high school level students.

In comparing 6th and 9th grade students' perceptions of presence, there were no statistical differences between these groups, suggesting they experienced similar levels of presence in the

VR environments. Although not significant, 6thgrade participants reported less control over the zSpace® environment (control question 1, $p = 0.041$), more difficulty with the 3-D environment responding to their actions (control question 2, $p = 0.021$), and stylus responsivity (control question 8, $p = 0.040$). In addition, they reported being more distracted by other students (distraction question 11, $p = 0.047$). Spronk and Jonkman (2012) found in their study exploring CL in younger learners that they have more difficulty suppressing distractions than adults, caused by fewer resources for self-control. They indicate this reduction in attention is due to high CL demands (e.g. multi-input sensory information) on the prefrontal cortex. CL and prefrontal cortex demand is of interest to this work as the latter cognitive structure was previously discussed as relating to the perception of presence (Miller & Cohen, 2001; Satoshi, 2008) and found to be underdeveloped in children (Baumgartner et al., 2008). This relationship is further complicated by CL research and its relationship to perceived control available to the learner (Swaak & de Jong, 2001). Other studies have also corroborated the cognitive effects such as “distraction, fatigue, and cognitive overhead in mastering the interface influence the outcome” with perceptions of presence (Roussos, Johnson, Moher, Leigh, Vasilakis, & Barnes, 1999, p. 258). Whereas in research using VR simulation training for medical students and doctors, the VR preparation imposed a lower CL than traditional cadaveric dissection (Andersen et al., 2016). Therefore, younger learners’ cognitive architecture may be less developed than other students resulting in different perceptions of presence with complex, multi-sensorial 3-D HE VR environments.

Cognitive Development and Perceptions of Presence

To explore the relationships between cognitive development and perceptions of presence, participants’ presence scores were compared to their performance on Piaget’s Inventory of

Developmental Tasks (IPDT). Significant positive correlations were found for 6th grade scores in the construct of laws and the subsets of rotation, angles, and matrices to their control presence score. This relationship suggests students who were better able to interpret physics concepts like spatial rotation and angular geometry on the IPDT reported more control of the 3-D, VR environment in the zSpace® session. A theory in which the human brain processes 3-D imagery is visuospatial constructive cognition, defined as one's ability to view the component parts of an object and construct a replica from those parts (Mervis, Robinson, & Pani, 1999). Mervis et al., (1999) argue that this ability may play a role in students' perceptions of presence as individual differences in visuospatial constructive ability and pattern-construction improved with age from children to adults. This may explain the lack of a relationship between laws and presence scores among the 9th grade students and the strong positive correlation between 6th grade students who scored highly in the highest range (ages 11-13) of the IPDT and presence control scores (Table 18). Also, there was a significant negative correlation between laws and distraction presence scores, suggesting that students who scored higher in the IPDT category of laws were less distracted. This finding may relate to previous work in flow theory where individuals who are more cognitively equipped to comprehend and navigate virtual environments, experience greater immersion and are less prone to visual or auditory distractions (Nordahl & Korsgaard, 2010). This research may shed light onto the significant negative relationship found between 6th grade students' scores in IPDT midrange (ages 9-10) questions (that contain subtests like levels, weight, perspective, rotation, shadows and distance) and distraction scores. For 9th grade, significant negative correlations were found between understanding relations (e.g. objects in series) and inclusion (e.g. nesting sets within sets) and sensory presence scores. This may be an artifact of cognitive chaining, where elementary mathematical operations like understanding a series are actually executed partially in parallel requiring a higher mental task, thus placing non-conscious strain on the brain and diverting cognitive resources away from other mental structures (Sackur & Dehaene, 2009). Moreover, significant negative correlations for 6th grade scores were found in weight and sensory presence. Piaget (1962) described the understanding of weight, like seriation, as a watershed moment in the transition from concrete operational development to formal operational thinking. This suggests if some students have yet to develop the cognitive architecture for abstraction (Satoshi, 2008), their sense of immersion suffers as greater mental effort goes to understanding the VR environment resulting in less sensory involvement. Witmer and Singer (1998) hypothesized sensory and distraction factors would affect both immersion and involvement in presence, therefore negative correlations in sensory and distraction (immersion) factors and positive correlations with control (involvement) found in this study help bolster their conjecture.

Open Ended Questioning and Cognitive Processes in 3-D HE VR Science Instruction

Perceptions of presence have been empirically linked to student engagement (Bulu, 2012; Jacobson, 2006; Dalgarno & Lee, 2010; Stull, Barrett, & Hegarty, 2013), yet coupling presence to learning has been elusive in 3-D HE VR learning experiences. Open-ended questioning permits a view into the cognitive learning activity and metacognitive processes of students while they are engaged in 3-D HE VR science instruction. Chi’s (2009) active-constructive-interactive framework generated a predictable taxonomy to explore students’ thoughts and actions while engaged in this module on cardiac form and function. In this study, both groups of students progressed in their questioning from activating prior knowledge, assimilating or encoding new knowledge (active) prior to instruction, restructuring or accommodating new knowledge (constructive) during instruction, to leveraging the expertise of the software and self-constructing knowledge well beyond the scope of the curriculum (interactive) after instruction. As a learner-centered framework, this permits delineation of mental activities undertaken by the learner in real-time. Sixth grade constructive questioning produced a significant negative correlation with distraction, suggesting they were more likely to construct knowledge from the curriculum when less distracted. Distraction has also been found to be a factor in other computer-based or technology-enhanced learning environments when students fail to engage in robust learning (Greene, Moos, & Azevedo, 2011). When compared to the Piagetian inventory, active questioning had significant negative correlations to sequence (6th grade) and relations (9th grade). Again, sequential computation is an early developmental milestone (Piaget 1962) suggesting if a student understood sequence, they were less likely to engage in active questioning and instead were more likely to participate in advanced constructive or interactive questioning. As reported, 9th grade students had a significant negative correlation between scores in IPDT relations and sensory presence; perhaps due to the diversion of mental resources for engagement in higher-level mental activities. This suggests that students who scored high in relations, which includes questions on sequence, seriation and inference, were less likely to engage in introductory-level active questioning and instead engaged in more sophisticated level questioning.

Constructive questions had significant negative correlations to rotation (6th grade) and sequence (9th grade). Again, significant positive correlations were found for 6th grade students' scores of Piagetian development in rotation and the virtual presence construct of control. This may provide additional insight to findings that students who are more apt in spatial rotation (and report more control of the 3-D, VR environment) engage in greater active questioning. As they perceive they are more in control, they may engage in lengthier time encoding or assimilating knowledge from the instruction. For 6th grade students, engagement in active questioning is developmentally appropriate, as younger children rely more on active experiences as their primary mode of acquiring knowledge (Wadsworth, 1996). In this study, 6th grade students asked many more active level questions than constructive and interactive questions compared to 9th grade participants. However, 9th grade students who already understood sequence, a developmental milestone achieved earlier in life (Piaget 1962), were more likely to engage in constructive questioning and instead in active questioning.

Interactive questioning had a significant positive correlation to sequence for 6th grade students and for probability, quantity, weight, and volume in 9th grade students. Ninth grade students who scored the highest in midrange questions (levels, weight, perspective, rotation, shadows, distance) and high range questions (volume, angles, classes, inclusion, inference, probability) had significant positive correlations to interactive questioning (Table 30). Since these significantly correlated categories include many aspects of 3-D VR environments (e.g. perspective, rotation, distance, weight, volume, angles, inference), students' proficiency in these subtests may have allowed for greater ability to construct new knowledge than those who were not as adept to utilizing the 3-D VR system.

Importance of Immersion and Presence in 3-D HE VR Science Instruction

Correlations between students' scores on a test of cardiac knowledge and presence indicates that immersion is a critical component of student learning in 3-D HE VR environments. For 6th grade students, gain scores were significantly negatively correlated with students' reports of distraction, suggesting interruptions in presence may affect younger students learning in 3-D HE VR experiences. In a study by Adams, Finn, Moes, Flannery, and Rizzo, (2009) students with ADHD were more distracted than those without ADHD with a significant impact on their learning in a VR classroom. Moreover, in other studies exploring phobia interventions in VR settings, children's presence scores for involvement were the sole factor that significantly predicted treatment effectiveness (Price, Mehta, Tone, & Anderson, 2011). However, in companion VR phobia studies, perceptions of involvement had not been prognostic for adults' treatment outcomes (Price & Anderson, 2007). Yet in work by Chen, Shih, and Yu, (2012) a lack of awareness to the passage of time (playfulness), played a key role in adults (teachers) acceptance of VR technology as a viable instructional tool. Clearly, immersion is key, but not the sole factor that ensures presence. According to Dalgarno and Lee (2010), "immersion relies on the technical capabilities of VR technology to render sensory stimuli, whereas presence is context dependent and draws on the individual's subjective psychological response to VR" (p. 13). As stated before, presence is dependent on several factors including the user's cognitive or affective state of mind (Slater, 2003).

Conclusion

In comparing combined assessments, overall zSpace® was an effective instructional tool for both 6th and 9th grade students. For content knowledge, 9th grade students appeared to have learned more, yet this finding is contingent on a few factors. First, the test of cardiac knowledge may have been too complex for this sample of 6th grade students as indicated in the low KR-20 calculation found in the pre-test administration (Table 2). This would complicate comparisons between and among groups with the other assessments. Second, the 6th grade students had a longer post-testing window for the test of cardiac knowledge, which may have affected their ability to recall information from their zSpace® session, impacting their post-test and gain scores. Next, this study suggests that in 3-D HE VR lessons, 6th grade students may experience less control over in VEs and greater distraction from outside sources. Both control and distraction influence an individuals' perceptions of presence (Witmer & Singer, 1998), and may have played a role in their learning of the cardiac form and function. Prior studies have indicated that discrepancies between vision and haptic cues can hinder user interaction with virtual objects (Arsenault & Ware, 2004; Ware & Rose, 1999). Furthermore, cognitive development was significantly related for both 6th and 9th grade students who engaged in the 3-D HE VR technology. Students who scored well on the Piagetian inventory reported greater presence (Table 18) and (9th grade) asked higher-level interactive questions on cardiac content (Table 30). Students' scores in specific areas of the IPDT involving spatial and mental rotation were positively correlated to increased perceptions of presence (Tables 14, 15, 17 and 18). This suggests that developmentally appropriate experiences may have played a significant role in the outcomes of this study. In particular, increasing their level of control while minimizing distractions may have facilitated presence for younger (6th grade) students. Virvou and Katsionis (2008) found with adolescent and younger learners they greatly rely on the VE to provide SRL scaffolding and support as a strategy to minimize frustration and distraction. Hence, developmentally appropriate use of 3-D HE VR technology is important, and an area needing further research. Aflalo and Graziano (2008) have shown with practice, neural structures could adapt to allow the user to navigate in a virtual environment whose topology does not exist in reality. Therefore, Aflalo and Graziano suggest that the cognitive machinery that negotiates spatial navigation is not a static map of the 3-dimensional world, instead a flexible process unique to spatial information that can facilitate new constructions of knowledge. Thus, repeated experiences with 3-D HE VR technology over time may be surprisingly beneficial for individuals with emerging cognitive development; both children (Price, Lee, & Malatesta, 2014) and adults with poor spatial ability (Merchant et al., 2013) who viewed 3-D images were able to draw more complex representations of that image than those who viewed the same image only in 2-D. In one study, users not only improved their understanding of college chemistry topics but also experienced development in their spatial ability (Merchant et al., 2012). A similar gain of spatial ability with students using 3D technology supports (compared to those who did not) has also been discovered in engineering education (Gutierrez, Dominguez, & Gonzalez, 2015).

Last, prior experiences interests may have had a considerable and confounding role in this research. As previously discussed, the prefrontal cortex is linked with personality (DeYoung et al., 2010), the latter of which is strongly correlated with interest (Ackerman & Heggestad, 1997). Witmer and Singer (1998) hypothesized that experiences of presence in virtual environments may be related to selective attention, or “the tendency to focus on selected information that is meaningful and of particular interest to the individual” (p. 226). Therefore personal judgements of meaning (Triesman, 1963; Triesman & Riley, 1969) may mediate content-related attributes (interest) and presence (Freeman et al., 1999). In comparing students’ test scores of cardiac knowledge to their performance on Piaget’s inventory (Tables 33 and 34), prior knowledge and developmental appropriateness played considerable roles for student learning in 3-D HE VR environments. Ninth grade students also had more interactive level questioning (Table 22) which relates to prior research establishing a relationship between learning task performance to learner’s prior knowledge (Wetzels, Kester, & van Merriënboer, 2011). Positive correlations were found in each of the five Piagetian task categories and pre-test scores for 9th grade students (Table 33). For 9th grade students, studying the human heart is within the standards for middle grade education (NC Essential Standards, 2010), indicating they likely had prior learning experiences with cardiac content. One indication of this was that very few 9th grade students, as compared to the 6th grade students, drew a symbolic heart when recalling the heart's shape from memory, a common misconception held by students with little to no background knowledge of cardiac anatomy (Allen, 2010, p.36). In research by Reiss et al., (2002) students had little appreciation of how organs existed as related structures within organ systems. The 15 year-old participants in their study had a better knowledge of their internal organs, yet most of them still revealed little understanding of their organ systems. Therefore, using 3-D HE VR technology for student learning of cardiac systems, students' questioning shows promise for learner understanding of the heart as an embedded component of a larger system.

The results of this research highlights a renewed importance of studying prior experiences in learning science; new activities build on previous experiences where children revise existing schema to accommodate or assimilate new information (Wadsworth, 1996). This has been shown in other research by Bakken et al., (2001) where "cognitive advances are more likely to occur when new activities are slightly different from those that the child has already experienced" and students were "actively engaged" (p. 60). In addition, research into prior experiences have been found influential on both individuals' interest (Özdilek & Calis, 2010) and attitudes (Hannigan, Hegarty, & McGrath, 2014) in science-based contexts. Provided individuals' perceptions of presence are thought to be strongly mediated by context (Ling et al., 2013; Mestre, 2015; Wallach, Safir & Samana, 2009; Weibel & Wissmath, 2011), these 3-D HE VR environments should capitalize on students' interests and prior learning experiences. Moreno (2006) found motivated students made complete use of their cognitive resources during learning. Therefore, if students are dedicating their cognitive resources to paying attention or keeping their interest (self-regulation) there is fewer mental ability available to learning the content in the VE (Moreno, 2009). Therefore, focus and learning should be specific to the student's interests, engaging and accommodating to younger learners intellectual requirements. For example, if a student is able to fully explore a realistic, beating human heart, as known by one with expertise in heart anatomy, they may focus on specific aspects of the heart's function minimalizing the reinforcement of common cardiac misconceptions (Badenhorst et al., 2015). Without cognitive preoccupation (e.g. attempting to sustain spatial understanding or motivation) the student may self-direct their learning experience, engage in the immersive VR experience and possibly garner long-term or life-long learning of cardiac function.

Best Practices in using 3-D HE VR Technologies in 6-12 Science Instruction

Instructional technology that employs 3-D, HE and VR capabilities, may have a unique ability to engage learners by replicating realistic structures or abstract phenomena from the minds of scientific experts. Research indicates that 3-D VR learning experiences "seem to make students feel more confident, more open, more participative, more creative, and more responsive" (Loureiro & Bettencourt, 2011, p. 2671). Therefore, incorporation of these systems may provide a more robust learning experience compared to students' sole attempts to cobble together complex information from traditional (e.g. verbal or visual) instruction. In a study by Jaakkola, Nurmi, and Veermans (2011) that taught students about electricity using VR technology, students with the greatest learning gains were those who utilized the VR simulation and real circuits in parallel than students who were given the computer simulation only.

The incorporation of technology enhanced learning environments continues to revolutionize K-12 science teaching and learning. This has fostered a paradigm shift from teacher-centered to student-centered activities where VEs may provide new opportunities for students to engage in structured, semi-structured and unstructured learning environments, empower them to freely explore and control their learning environment, and author their conditions for learning (Freitas & Neumann, 2009). As students directly interact with instructional technology within this new paradigm, users may directly manipulate interfaces with action properties analogous to their real-world counterparts. Through thoughtful and careful built-in scaffolding by curricular designers, the student can act as Pea (1993) described “the Piagetian metaphor of ‘child as scientist’ – he or she could be scaffolded in the achievement of activity…now embedded in the constraints of the artifacts with which the child was playing” (p. 65). It is clear there are significant future challenges in proper pedagogical design and building models of how students learn in 3-D, virtual reality environments (Fowler, 2015). From this work, it is evident that students should be developmentally ready to understand the abstract, spatial world of 3-D HE VR environments to best reap the benefits of deep involvement (control) and immersion (lack of distraction). This includes creating software content that best suites the interests and prior knowledge held by the students at that grade band to maximize understanding of complex scientific phenomena. This should include a reduction of seductive details, defined as irrelevant additional materials found in VR environments, which have a detrimental effect on student learning by needlessly increasing CL demands (Park, et al., 2011, p.6). Work by Patterson and Silzars (2009) found individuals who had trouble viewing virtual objects in 3-D VR space resulted in negative effects on their learning and comfort. They suggested “cognitive engineering” as a strategy to build mental scaffolds for understanding VR spatial relationships. Continued research in this field demonstrates the promise and possible pitfalls of this technology in science instruction and its affordances for younger learners.

Recommendations for Future Research

Researchers warn that students' (as compared to adults) inability to adequately state or recall their subjective level of presence, either due to developmental factors or novelty of instructional technology, may skew self-report data introducing threats to validity (Azevedo, 2015). However, work by Prayeetha, Deighton, Fonagy, Vostanis, & Wolpert (2014) examined self-report data in children found high validity and reliability with participants as young as eight years of age triangulating with other objective data resources. In presence work by Childers and Jones (2015), students used a self-report measure to evaluate their perceptions of presence while participating in a remote microscopy experiment. Based upon this work, they found students reported more realness (e.g. presence) when using the technology than their teachers. Also, this work in remote microscopy has demonstrated differential outcomes for presence and science identity (Childers & Jones, 2014), future work is needed to explore how 3-D, VR environments elicitation of presence influence, identity and other affective states (e.g. interest and motivation).

A surprising finding from the present study was the lack of differentiated perceptions of realism between 6th and 9th grade groups. It is known that the level of realism in heart representations has a differential effect on student achievement (Dwyer, 1972) and perceptions of realism is directly correlated to the level of sophistication within the cognitive architecture of the prefrontal cortex (Fuster, 2008; Miller. & Cohen, 2001). However, Hartford and Good (1976) have indicated from validation sampling that only half of eleventh and twelfth grade science students are formal operational thinkers (Patterson & Milakofsky, 1980). Therefore, cognitive homogeneity of the sample may have played a role in this finding. This suggests future research should focus on primary students' perceptions of presence as it relates to their level of (Piagetian) cognitive development. As these systems become incorporated into K-12 science classrooms, concurrent research is needed to explore how users rank these novel experiences against and in parallel with traditional science instructional approaches. Investigations should include how these varied pedagogical approaches are preferred by the learner as well as increases their understanding of the science topic under study.

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Footnotes

[1] Cognitive Dimensions of Piaget's Inventory of Developmental Tasks refers to 5 constructs and their 3 to 4 respective subtest areas (*N* = 72).

[2] The five major constructs of the Inventory of Piaget's Developmental Tasks (IPDT) include questions on laws (*N* = 12), relations (*N* = 16), conservation (*N* = 16), images (*N* = 16), and classification (*N* = 16).

[3] Subtests of the Inventory of Piaget's Developmental Tasks (IPDT) include questions on rotation (*N* = 4), angles (*N* = 4), probability (*N* = 4), sequence (*N* = 4), seriation (*N* = 4), inference (*N* = 4), quantity (*N* = 4), weight (*N* = 4), volume (*N* = 4), distance (*N* = 4), levels (*N* = 4), perspective (*N* = 4), movement (*N* = 4), shadows (*N* = 4), matrix (*N* = 4), symbols (*N* = 4), classes (*N*=4), and inclusion (*N* = 4).

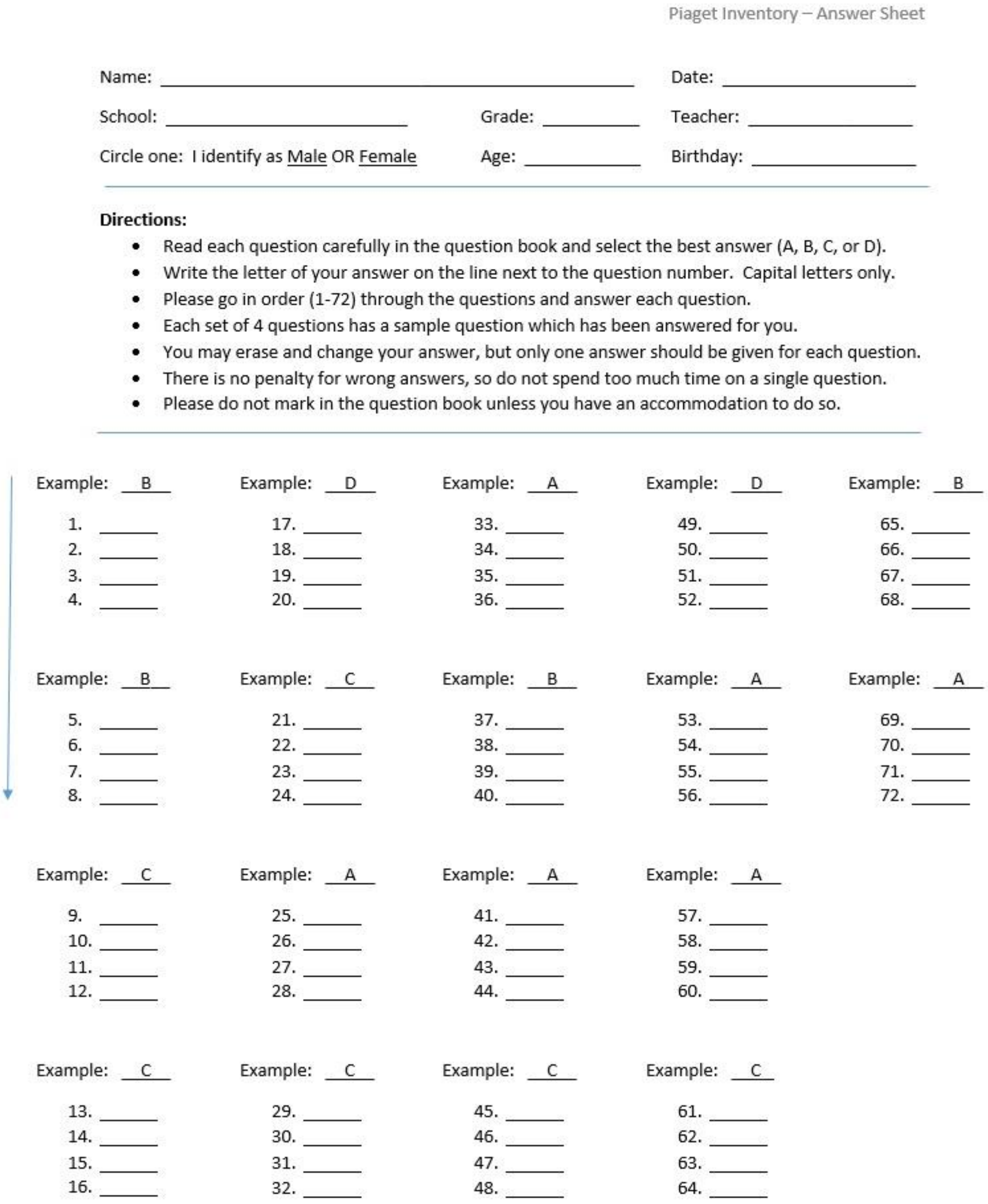
[4] Cognitive classifications of the Inventory of Piaget's Developmental Tasks (IPDT) include questions by age proficiency. Seven to eight year old children are typically proficient in the low range questions (*N* = 24), nine to ten years are typically proficient in midrange questions (*N* = 24), and eleven to thirteen year olds are typically proficient in the high range questions (*N* = 24).

[5] Learning Activities refer to the conceptual framework for differentiating learning activities designed by Chi (2009). The three categories are active, constructive and interactive activities.

APPENDICES

Appendix A – Inventory of Piaget's Developmental Tasks (IPDT), 72 items

NOTE: The inventory is under copyright and cannot be reproduced here.



Piaget Inventory – Answer Sheet

Name: ______________________________ Date: ______________

School: ________________ Grade: ________ Teacher: ____________

Circle one: I identify as Male OR Female Age: ________ Birthday: ____________

Directions:

- Read each question carefully in the question book and select the best answer (A, B, C, or D).
- Write the letter of your answer on the line next to the question number. Capital letters only.
- Please go in order (1-72) through the questions and answer each question.
- Each set of 4 questions has a sample question which has been answered for you.
- You may erase and change your answer, but only one answer should be given for each question.
- There is no penalty for wrong answers, so do not spend too much time on a single question.
- Please do not mark in the question book unless you have an accommodation to do so.

Example: B

1. ______
2. ______
3. ______
4. ______

Example: B

5. ______
6. ______
7. ______
8. ______

Example: C

9. ______
10. ______
11. ______
12. ______

Example: C

13. ______
14. ______
15. ______
16. ______

Example: D

17. ______
18. ______
19. ______
20. ______

Example: C

21. ______
22. ______
23. ______
24. ______

Example: A

25. ______
26. ______
27. ______
28. ______

Example: C

29. ______
30. ______
31. ______
32. ______

Example: A

33. ______
34. ______
35. ______
36. ______

Example: B

37. ______
38. ______
39. ______
40. ______

Example: A

41. ______
42. ______
43. ______
44. ______

Example: C

45. ______
46. ______
47. ______
48. ______

Example: D

49. ______
50. ______
51. ______
52. ______

Example: A

53. ______
54. ______
55. ______
56. ______

Example: A

57. ______
58. ______
59. ______
60. ______

Example: C

61. ______
62. ______
63. ______
64. ______

Example: B

65. ______
66. ______
67. ______
68. ______

Example: A

69. ______
70. ______
71. ______
72. ______

Appendix B – Test of Cardiac Knowledge (30 Questions)

Content Assessment – Human Heart **Pre _______ Post ________**

Name: ____

<u>Directions</u>:
Please answer the following 30 questions to the best of your ability.
Please answer each and every question before proceeding to the next one.
If you do not know the answer, make your best guess.
You may write on this test.

1. Draw a picture of a heart and place the number of the identified parts where they would located on the heart.

1. Superior vena cava
2. Aorta
3. Pulmonary vein
   Ventricle
4. Pulmonary artery
5. Inferior vena cava

6. Right Atrium
7. Left Atrium
8. Right
9. Left Ventricle

10. There are **<u>4 valves</u>** in the heart.

Place a ★ where you think each valve is located. <u>You should have 4 stars total</u>.

<u>Directions</u>: Once you are finished with question 1, do <u>not</u> look back to Question 1 or change any part of your answer.

Please continue to the rest of the test.

<u>Directions</u>: For the <u>Multiple choice questions</u> (A, B, C, D), circle on the test the letter of your answer.

2. The blood, blood vessels and the heart are all parts of what body system?
    - A) The Lymphatic System
    - B) The Circulatory System
    - C) The Respiratory System
    - D) The Integumentary System

3. The human heart has how many chambers?
   A) One B) Two C) Three D) Four

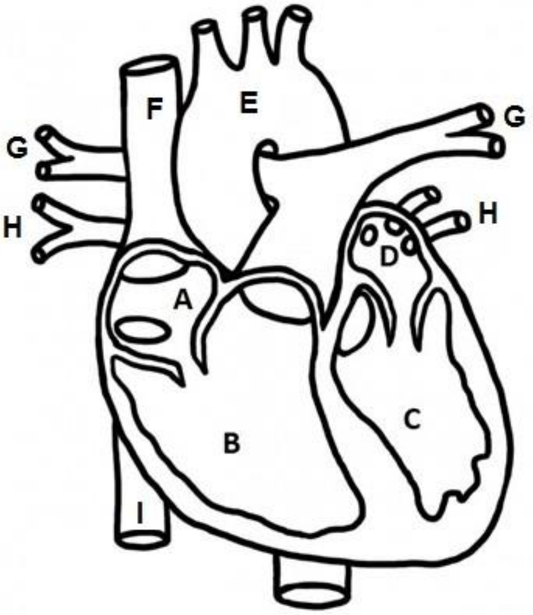
4. *True or False*? The aorta is the largest artery in the human body. *Write your answer here*: _____

A picture of the heart is shown below.

I) Read each term carefully.

II) Write the letter (A, B, C, D, E, F, G, H, or I) on the line that correctly matches the part of the heart.
Note, each letter will only be used once.

5. "Right Ventricle." _____________
6. "Left Ventricle." _____________
7. "Left Atrium." _____________
8. "Right Atrium." _____________
9. "Aorta." _____________
10. "Inferior Vena Cava." _____________
11. "Pulmonary Vein." _____________
12. "Superior Vena Cava." _____________
13. "Pulmonary Artery." _____________



14. The size of the human heart is approximately the same size as what other body part?
    A) Foot B) Fist C) Face D) None of these

15. Blood would most likely enter though the inferior vena cava from which location?
    A) Leg B) Arm C) Lungs D) Head

16. Blood from which location would most likely enter the heart through the pulmonary vein?
    A) Leg B) Arm C) Lungs D) Head

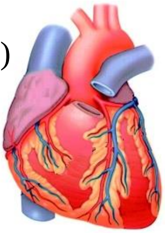
17. If oxygenated blood is unable to leave the heart, there is likely a problem in which blood vessel?
    A) Aorta C) Superior Vena Cava
    B) Pulmonary artery D) Inferior Vena Cava

18. The pulmonary artery is unique from other arteries because it…
    A) Moves blood away from the heart. C) Carries oxygenated blood.
    B) Moves blood to the heart. D) Carries deoxygenated blood.

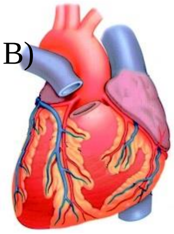
The image shown right is two different views of the same skeleton.

19. Which picture shows the correct orientation of the heart if you placed it in the chest of the **skeleton A**?

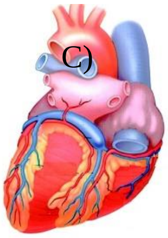
A)



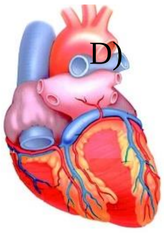
B)

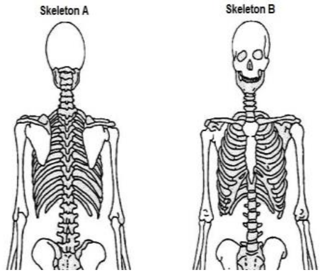


C)



D)

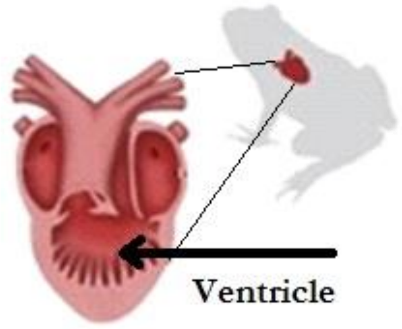




Explain why you chose your heart:

____

20. The heart-beat (the sound you hear or feel when taking your pulse) is made by which of the following?
    A) Contraction of the heart muscle C) Closing of the heart valves
    B) Emptying of the veins D) Draining of the arteries



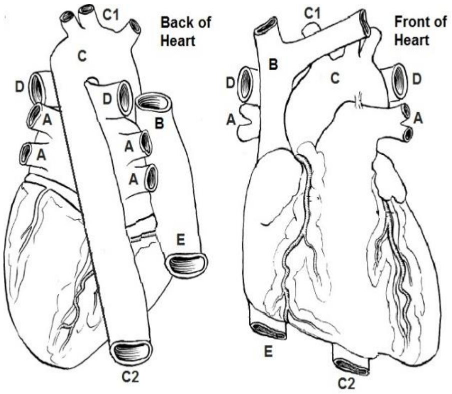
The amphibian heart from a frog, is shown here, left.

21. What is the consequence of having 1 single ventricle as compared to having 2 in the human heart?

A) The atria would leak blood back into the ventricle.
B) The heart would not contract with as much force.
C) The lungs would not as effective in oxygenating blood.
D) Oxygenated blood and deoxygenated blood would mix in the ventricle.

22. The role of each atrium is to…?
    - A) Pump blood out of the heart.
    - B) Receive blood coming into the heart.
    - C) Serve as a doorway between chambers.
    - D) Connect the heart to the lungs.

The image below is two different views of the same heart.
Use it to answer the following three questions.



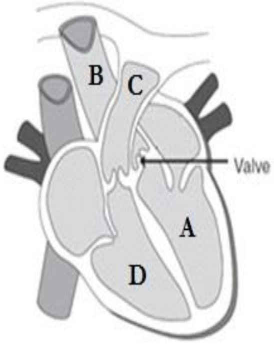
23. Write the letter on the line below where **blood from the lungs enters into the heart**. _________

24. Describe blood flow at letter **C2**.
A) To the neck and head C) To the legs and feet
B) From the neck and head D) From the legs and feet

25. Describe blood flow at letter **E**.
A) To the neck and head C) To the legs and feet
B) From the neck and head D) From the legs and feet

26. When the heart contracts, the …?
    - A) The two ventricles contract first, then the two atria.
    - B) The two atria contract first, then the two ventricles.
    - C) The right side of the heart contract first, then the left side.
    - D) The left side of the heart contract first, then the right side.

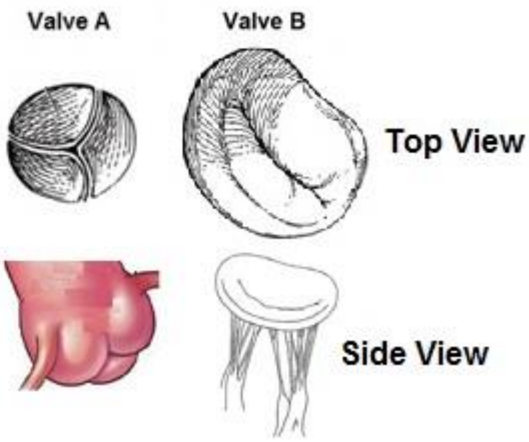
This heart, shown right, has been turned to glass for question 27. (Note the area *shown with an arrow*.)



27. If the heart was actively beating, what would happen if this valve could <u>not</u> properly close?
    - A) Blood would leak back into the part labeled A.
    - B) Blood would pump into the part labeled B.
    - C) Blood would pump into the part labeled C.

D) Blood would leak back into the part labeled D.

The two different types of heart valves are shown below. They are not to scale. Use them to answer question 28.



28. Based on its shape, which of these valves would function to allow blood to enter or flow into of the heart?

A) Valve A
B) Valve B
C) Both of these
D) None of these

Explain why you believe your valve is an "entrance" valve:

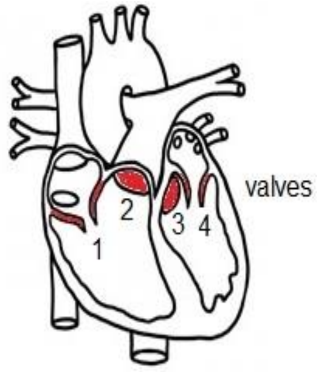
____

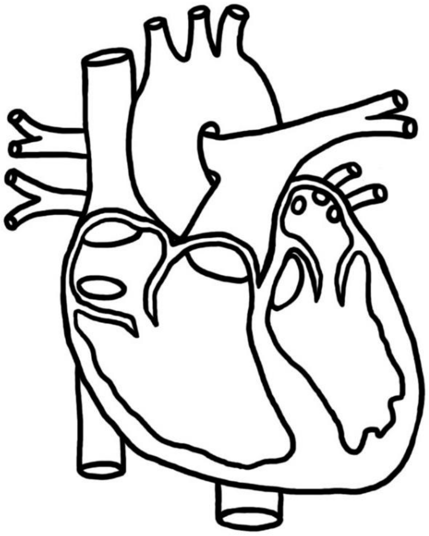
Use the picture of the heart, below, to help you answer question 29.

29. Which numbered pair best describes how the 4 heart valves work together in this sentence?

Valves __________ open first and close at the same time, allowing blood to into the heart where valves __________ open and close for blood to exit the heart.

A) 1 and 4; 2 and 3
B) 2 and 3; 1 and 4
C) 3 and 4; 1 and 2
D) 1, 2, 3 and 4; 1, 2, 3 and 4





*Use the heart picture, left, to **draw arrows** of blood flow through the heart to answer question 30.*

30. Trace with your colored pens the movement of blood.

A) Using your **blue** pen… start from the body and into the heart drawing arrows to the lungs.

B) Using your **red** pen… drawing arrows from the lungs back into the heart, through the heart and out to the body.

Explain your drawing:

____

END OF ASSESSMENT

Appendix C – Three question prompt on cardiac form and function

Name: ________________________________ Period: _________ Date: ___________

Pre zAnatomy:

When you think about the structure and function of the human heart, what you like to know more about? Please list at least 1 question.

Post zAnatomy / Pre zExperience Heart:

Now that you have had time to explore the heart, what would you like to know more about the structure or function of the human heart? Please list at least 1 question.

Post zExperience Heart:

Know that you have had time to explore the heart, what would you like to know more about the structure or function of the human heart? Please list at least 1 question.

Appendix D – zAnatomy® Tutorial

Slide	***Content***	***Virtual Task***
Introduction Part 1/8	The circulatory system delivers blood to all parts of the body. It is made up of the blood vessels, blood, and the heart.	Picking up, Rotation
The Size of your Heart Part 2/8	The heart is actually a muscle about the size of your fist that pumps blood to your body through blood vessels. Try resizing the heart to be the size of your fist, so you can see how big your heart is.	Zooming
Color-coding the heart Part 3/8	To understand the heart better, we will color parts of the heart red and blue. The color red is used to show the parts of the heart and blood vessels which have oxygenated blood in them. And the color blue is used to show the part which have deoxygenated blood in them. In reality, deoxygenated blood isn't really blue. It is a dark shade of red.	Color change, Rotation
Blood Vessels Part 4/8	Blood vessels are divided into arteries, which carry blood from the heart to the rest of the body, and veins, which carry blood from the body to the heart. There are 5 main blood vessels that connect directly to the heart.	
	1. Superior vena cava – The SVC brings deoxygenated blood from the top half of your body, including your arms, into the right side of your heart.	Just arrow
	2. Inferior vena cava – bring deoxygenated blood from the lower half of your body including your legs, into the right side of the heart.	Just arrow
	3. Pulmonary Vein – The pulmonary vein carries oxygenated blood from the lungs, into the left side of the heart. I. MORE – Viewing the heart from the back, you'll notice how the pulmonary vein splits in two directions, one branch comes from the left lung and the other branch comes from the right lung.	Blood animation

	II. MORE – The Pulmonary vein is special because it is the only vein that carries oxygenated blood. All other veins carry deoxygenated blood.	
	4. Pulmonary Artery – The pulmonary artery carries oxygenated blood away from the right side of the heart and into the lungs. I. MORE – Viewing the heart from the back, you'll notice how the pulmonary artery splits in two directions, one branch goes to the left lung and the other branch goes to the right lung. II. MORE – The Pulmonary artery is special because it is the only artery that carries deoxygenated blood. All other arteries carry oxygenated blood.	Flashes
	5. Aorta – The Aorta, which is the largest artery in the body, carries blood away from the left side of the heart out to the rest of the body. I. MORE – Notice how the Aorta branches out to bring oxygenated blood to all the parts of the body.	Flashes
Dissect the Heart Part 5/8	To see inside of the heart, we must dissect the heart.	Make several incisions Cross section of heart now visible
Chambers of the Heart Part 6/8	There are four chambers in the heart: Two on the right that pump deoxygenated blood, and two on the left that pump oxygenated blood..[sic] Keep in mind that this heart belongs to someone who is facing you, so their right side is your left and their left side is your right.	
	1. Right Atrium – The right Atrium, on the top-left, takes in deoxygenated blood from the superior and inferior vena cava. When the right atrium contracts, it pushes blood into the right ventricle.	Flashing, Blood animation
	2. Right Ventricle - The right Ventricle, on the bottom-left, takes in blood from the right atrium. When the right ventricle contracts, it pushes blood out to the pulmonary artery, and out to the lungs.	Flashing, Blood animation
	3. Left Atrium – The left Atrium, on the top-right, takes in oxygenated blood returning from the lungs through the Pulmonary vein. When the left atrium contracts, it pushes the blood down to the left ventricle.	Flashing, Blood animation

	4. Left Ventricle – The left Ventricle, on the bottom-right, takes in oxygenated blood from the left atrium. When the left ventricle contracts, it pushes blood out the Aorta to the rest of the body.	Flashing, Blood animation
	5. Valves – Dividing the 4 chamber of the heart are one-way doors called values, which keep the blood flowing forwards. I. MORE – One valve, acting as the entrance, opens to let the blood flow in while the exit valve is closed. II. MORE - Then the entrance shuts tight, the exit values opens, and the heart muscle squeezes to push the blood into the next chamber. III. MORE – And finally the exit value shuts and the cycle repeats.	All 4 valves are flashing, Pointing labels as “valves”
Your Heartbeat Part 7/8	When you listen to your heart beat, the sounds causes by the quick closing of valves inside your heart.	Haptic Feedback, Heart is visible Valves are now animated in real time
Lesson Complete Part 8/8	Lesson Complete (Heart now whole)	Rotation

Appendix E – Presence Survey

Presence Survey

Directions: Please darken the bubble that best addresses the subject of the question.

1. What is your age? ○ 11 ○ 12 ○ 13 ○ 14 ○ 15 ○ 16 ○ 17 ○ 18
2. I identify myself as a? ○ Female ○ Male
3. What best describes your ethnicity? ○ Hispanic or Latino or Chicano
   ○ Not Hispanic or Latino or Chicano

4. What best describes your race? *You may bubble more than one.*
   - ○ American Indian or Alaska Native
   - ○ Asian
   - ○ Black or African American
   - ○ Native Hawaiian or Other Pacific Islander
   - ○ White

Technology Use Inventory

Directions: Read each statement carefully. Circle the correct response for each statement.

1. I use a computer at least once a week. YES NO
2. I use an iPad/Tablet at least once a week. YES NO
3. I use the Internet at least once a week. YES NO
4. I play video games and/or computer games at least once a week. YES NO

Presence Survey

Directions: Read each statement carefully. Please write the number on the line provided next to the question that best represents how you feel when using zSpace®.

Strongly Disagree	Disagree	Slightly Disagree	Slightly Agree	Agree	Strongly Agree
1	2	3	4	5	6

CONTROL FACTORS

____1. I felt that I was in control of zSpace® 3D environment during the session.
____2. zSpace® 3D environment would respond to my actions.
____3. zSpace® 3D environment did what I wanted it to do.
____4. The interactions I had with the zSpace® 3D environment were natural.
____5. I felt that the stylus allowed me to control what was occurring in the 3D environment.
____6. The stylus would do what I wanted it to do in the 3D environment.
____7. The interactions I had with the stylus to interact with the 3D environment were natural.
____8. The stylus would respond to my actions when I interacted with the 3D environment.
____9. The stylus allowed me to control the movement of objects in the zSpace® environment.
____10. I was able to predict what would happen if I moved an object in the 3D zSpace® environment.
____11. I could move objects easily in the 3D zSpace® environment.

____12. I could manipulate (handle) objects easily in the 3D zSpace® environment
____13. There was a delay between what I wanted to do and what happened on the screen.
____14. I adjusted quickly to the screen during the zSpace® session.
____15. I could easily move objects in the 3D environment.
____16. I could easily interact with different objects in the 3D environment.
____17. I could manipulate objects with a stylus in ways that I could not in the real world.
____18. I could easily zoom in on objects.
____19. I could easily zoom out from an object.
____20. I could navigate inside of objects using the stylus.
____21. I was able to navigate behind objects that I could not do normally in a 2D (like a flat screen) simulation.

SENSORY FACTORS

____1. My sense of sight was highly engaged during the session.
____2. My sense of hearing was highly engaged during the session.
____3. My sense of touch was highly engaged during the session.
____4. I was convinced that the objects I viewed with zSpace® were moving through space.
____5. I was able to explore all of the 3D environment with my sight.
____6. I was able to explore all of the 3D environment with my sense of touch.
____7. I was able to closely examine objects during the zSpace® session.
____8. I was able to closely examine objects from multiple viewpoints during the zSpace® session.

DISTRACTION FACTORS

____1. I was aware of other events in the classroom during the zSpace® session.
____2. I was aware of sounds outside of the zSpace® session.
____3. I was aware of the stylus I used to control objects in zSpace®.
____4. I was aware of the 3D glasses I used to view objects in zSpace®.
____5. I was aware of the zSpace® computer screen I used to view objects in zSpace®.
____6. I was aware of the zSpace® camera during the session.
____7. I was very involved during the zSpace® session.
____8. The 3D glasses were distracting.
____9. The stylus was distracting.
____10. The 3D objects in the zSpace® environment were distracting.
____11. Other students were distracting me during the zSpace® session.
____12. The stylus interfered when I moved objects in the 3D zSpace® environment.
____13. The glasses interfered when I moved objects in the 3D zSpace® environment.
____14. I was able to concentrate easily during the zSpace® session.
____15. I was comfortable using the stylus during the zSpace® session.
____16. I was comfortable using the 3D glasses during the zSpace® session.
____17. I felt comfortable viewing the objects in the 3D zSpace® environment.

REALISM FACTORS

____1. The zSpace® 3D objects were not realistic.
____2. I felt disconnected during the zSpace® session.
____3. My experiences during the zSpace® session were similar to real laboratory experiences.

____4. The 3D zSpace® environment was realistic.
____5. I felt disoriented when I put the stylus down.
____6. I felt confused when I put the stylus down.
____7. I felt disoriented when I removed the 3D glasses.
____8. I felt confused when I removed the 3D glasses.
____9. I lost track of time during the zSpace® session.
____10. I could transition from the real world to using zSpace® easily.
____11. The illusion of the 3D zSpace® environment was very real to me.
____12. The object appeared to jump out of the zSpace® screen.
____13. Using zSpace® to view objects is more realistic than using a simulation on a computer.
____14. Using zSpace® to view objects is more realistic than watching a video.
____15. Using zSpace® to view objects is more realistic that participating in lab at school.

Appendix F – Scoring Rubrics and Answer Key for the Test of Cardiac Knowledge

Important note: Must score heart either as ***forward*** (front) facing or ***rear*** (the back) facing heart

	0	**1**	**2**	**3**	**4**	**Totals per image:**
Shape	A heart symbol	A modified heart symbol	Any rounded symmetrical shape (no indication of a symbolic heart)	Rounded asymmetrical structure	Accurate and semi-accurate heart shape (asymmetrical with bottom part larger than the top)	
Systems Thinking	No indication of outside structures	Lines are drawn outside of heart structure	Indication of vessels (tubes) but randomly moving out	Indication of vessels on some (2) but not all sides (4) of the heart	Indication of vessels on all sides (4) of the heart	
Valves (STARS)	No valves or all are outside the heart (not affiliated with a vessels or tube indication OR serving as a barrier)	Valves are inside the heart (not affiliated with a vessel or tube indication OR serving as a barrier)	Valves are inside the heart (some affiliated with a vessel or tube indication AND serving as a barrier)	valves are inside the heart, but only half (2) of the valves have a correct location (chambers)	All four valves in correct/logical locations (4 chambers)	
Veins / Vessels (#1-5)	no labeled blood vessels	0 sets correct of Vena cava, aorta and pulmonary blood vessels	1 set correct of Vena cava, aorta and pulmonary blood vessels	2 sets correct of Vena cava, aorta and pulmonary blood vessels	All 3 sets of Vena cava, aorta and pulmonary blood vessels	
Chambers (#6-10)	no labeling of chambers	Labels are incorrect but inside of the heart	Atria and ventricles are flipped and inverted	Atria and ventricles are flipped only (left/right incorrect)	accurate atria and ventricle positioning (left/right correct)	
					Total Score /20	______________

Response Type	**0**	**1**	**2**	**3**	**4**	*Totals per Concept*
Blood circulation TO the heart (the Blue Pen)	no response	Begins in the wrong location, arrows going the wrong way, no clear movement	Correctly traces from LA to LV (wrong side of the heart)	Correctly traces from RA to RV (ignoring SVC/IVC)	Correctly traces through SVC/IVC to RA, RV	
Cardiopulmonary (Heart-Lung-Heart)	no response	Incorrect - no indication of movement to and from lungs	Indicates that blood leaves to the lungs through PV or PA (not labeled), return from lungs is unclear	Correctly traces out to Lungs with opposite return (not properly labeled) only one side	Correctly traces out to Lungs (PV) and opposite return (PA) (correctly labeled)	
Blood circulation FROM the heart (the Red Pen)	no response	Begins in the wrong location, arrows going the wrong way, no clear movement	Correctly traces from RA to RV (wrong side of the heart)	Correctly traces from LA to LV (ignoring Aorta)	Correctly traces through LA to LV, out of Aorta	
					Total Score /12	________________

Answer Key for Selected Response Items:

2. B
3. D
4. TRUE
5. B
6. C
7. D
8. A
9. E
10. I
11. H
12. F
13. G
14. B
15. A
16. C
17. A
18. D
19. C
20. C
21. D
22. B
23. A
24. C
25. D
26. B
27. A
28. B
29. A