A Review and Selective Analysis of 3D Display Technologies for Anatomical Education

Matthew Hackett
University of Central Florida

A REVIEW AND SELECTIVE ANALYSIS OF 3D DISPLAY TECHNOLOGIES FOR ANATOMICAL EDUCATION

by:
MATTHEW G. HACKETT
BSE University of Central Florida 2007,
MSE University of Florida 2009,
MS University of Central Florida 2012

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ABSTRACT

The study of anatomy is complex and difficult for students in both graduate and undergraduate education. Researchers have attempted to improve anatomical education with the inclusion of three-dimensional visualization, with the prevailing finding that 3D is beneficial to students. However, there is limited research on the relative efficacy of different 3D modalities, including monoscopic, stereoscopic, and autostereoscopic displays. This study analyzes educational performance, confidence, cognitive load, visual-spatial ability, and technology acceptance in participants using autostereoscopic 3D visualization (holograms), monoscopic 3D visualization (3DPDFs), and a control visualization (2D printed images). Participants were randomized into three treatment groups: holograms (n=60), 3DPDFs (n=60), and printed images (n=59). Participants completed a pre-test followed by a self-study period using the treatment visualization. Immediately following the study period, participants completed the NASA TLX cognitive load instrument, a technology acceptance instrument, visual-spatial ability instruments, a confidence instrument, and a post-test. Post-test results showed the hologram treatment group (*Mdn=80.0)* performed significantly better than both 3DPDF (*Mdn*=66.7, p=.008*)* and printed images (*Mdn*=66.7, p=.007). Participants in the hologram and 3DPDF treatment groups reported lower cognitive load compared to the printed image treatment ($p < .01$). Participants also responded more positively towards the holograms than printed images (p < .001). Overall, the holograms demonstrated significant learning improvement over printed images and monoscopic 3DPDF models. This finding suggests additional depth cues from holographic visualization, notably head-motion parallax and stereopsis, provide substantial benefit towards understanding spatial anatomy. The reduction in cognitive load suggests monoscopic and autostereoscopic 3D may utilize the

visual system more efficiently than printed images, thereby reducing mental effort during the learning process. Finally, participants reported positive perceptions of holograms suggesting implementation of holographic displays would be met with enthusiasm from student populations. These findings highlight the need for additional studies regarding the effect of novel 3D technologies on learning performance.

I would like to dedicate this dissertation to my wife, Kristen, for her unwavering support and love throughout this long endeavor. I would also like to thank my Mom and Dad, for always encouraging me, and making me feel like I could do anything to which I set my mind. Finally, to my children, Matthew and Alice, thank you for always reminding me of what's most important in life, putting a smile on my face, and serving as a terrific excuse to give my advisor when I haven't made any progress.

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CHAPTER 1: INTRODUCTION

The understanding of anatomy is a key component to all medical professions. Ranging from first responders, such as emergency medical technicians (EMT), to highly skilled physicians, anatomy forms a significant portion of the necessary knowledge foundation. Anatomy is defined as the science of various structures that comprise the human organism (Gray, 1918), from a macro to a micro level. The complementary study of physiology is of equal importance. Unlike anatomy, physiology is the science of body functions, or how a living organism works. This ranges from the study of individual molecular activity, such as cellular respiration, to the interplay of organ systems, such as the interaction between the nervous system and the cardiovascular system (Widmaier, Raff, & Strang, 2006). A thorough knowledge of both anatomy and physiology is necessary to have a complete understanding of the human body, as form and function are deeply interrelated.

Since it is such a crucial component to practicing medicine, anatomical training is common during education for a vast array of medical practitioners. In the civilian world, the National Institute of Health (NIH) has broadly split medical professions into five broad categories: primary care, nursing care, drug therapy, specialty care, and immediate care. Primary care consists of medical doctors (MDs), physician assistants (PAs), and nurse practitioners (NPs) who treat day to day healthcare issues. Nursing care includes registered nurses and licensed practice nurses, who work in conjunction with higher echelon medical professionals. Drug therapy contains pharmacists, who process drug prescriptions and instruct safe and effective drug administration. Specialty care includes all medical specialists, such as surgeons, oncologists, radiologists, dermatologists, etc. (Vorvick, 2012). The National Highway Traffic Safety Administration describes immediate care, or point of injury care, as initial treatments provided by emergency medical services (EMS) such as emergency medical responders, EMTs, and advanced medical technicians (NHTSA, 2009). A similar classification exists in the military sector defined by the Army Techniques Publication on Casualty Care, ATP 4-02.5, with primary care, nursing care, drug care, and specialty care all performing the same roles as their civilian counterparts ("ATP 4-02.5," 2013). Emergency care within the military is provided by Combat Medics and Combat Life Savers. Combat Life Savers are closely related to emergency medical responders and have proficiency in a limited number of treatments. Combat Life Saver skills primarily focus on skills to stabilize a casualty. Combat Medics train in a wider range of medical treatments, akin to EMTs, as defined by the Combat Medic Handbook (Army, 2009).

Despite the variety in medical professions, the underpinning of each includes training in anatomy. However, it is important to realize that the extent of the anatomy training differs significantly. For example, an EMT or Combat Medic requires general understanding of the major organ systems including the nervous, respiratory, musculoskeletal, endocrine, and circulatory systems, but the digestive, urinary, and reproductive systems are beyond the scope of training (EMT-Training, 2008). Nurses and PAs require knowledge of the entire human body, with each organ system being covered more extensively. Additionally, at this level, knowledge of embryology and cytology, is required (Vanderbilt, 2014). Finally, MDs, PAs, and NPs require extensive knowledge in all of the subdisciplines of anatomy (Table 1), with intensive study during specialization. For example, neuro-surgeons require specialized training in neuroanatomy, including cortical anatomy, three-dimensional (3D) sub-cortical and deep brain anatomy, ventricular, and cisternal anatomy (Dare & Grand). The overarching theme is that all health professions require a thorough understanding of the anatomy in order to provide the best possible care.

Table 1: Selected Subdisciplines of Anatomy

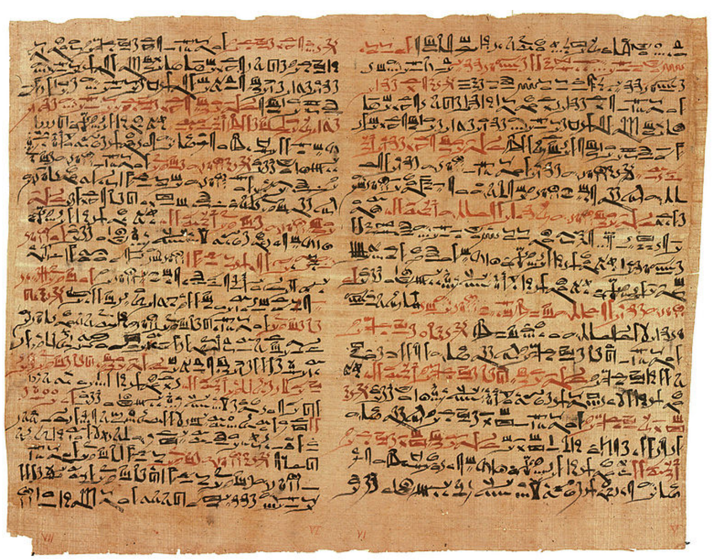
Subdisciplines of Anatomy	Study of
Embryology	Structures that emerge from the time of the fertilized egg through the eighth week in utero
Developmental Biology	Structures that emerge from the time of the fertilized egg to the adult form
Histology	Microscopic structure and organization of tissues
Surface Anatomy	Anatomical landmarks on the surface of the body through visualization and palpation
Gross Anatomy	Structures that can be examined without using a microscope
Systemic Anatomy	Structure of specific systems of the body such as nervous or respiratory systems
Regional Anatomy	Specific regions of the body such as the head or chest
Cytology	Physical properties, structure, and organelles of cells
Pathological Anatomy	Structural changes (from gross to microscopic) associated with disease
Radiographic and Imaging-Based Anatomy	Body structures that can be visualized with X-Rays or other medical imaging modality

Source: (Derrickson & Tortora, 2006)

The focus of this dissertation is the delivery of anatomical education, specifically using technology to visualize anatomy. Presented herein is a brief summary of historical anatomical instruction, followed by current educational practice, and the challenges facing anatomical education. The background presented within this chapter will establish the foundation and motivation for this dissertation research.

History of Anatomy

Imparting the understanding of anatomy has been a challenge posed to teachers and medical professionals for thousands of years. The first key to teaching anatomy was to understand the human body. Anatomists have long studied the human body trying to determine the form, and subsequently deduce the function. The earliest known anatomists and physicians were based in Egypt, starting with Hesy-Ra (Selin & Shapiro, 2003) and Imhotep (Osler, 1921) in mid-27th century BC. Egyptian physicians and anatomists gathered information including knowledge of non-invasive surgery, bone setting, and pharmacology. Much of this knowledge was based on their understanding of anatomy, which included the heart, liver, spleen, kidneys, hypothalamus, uterus, bladder, and blood vessels (Porter, 1999). The Egyptians knew spreading this knowledge was necessary. To accomplish this, the Egyptians used Papyrus to record descriptions of anatomical content. The oldest, dating to ca 1600 BCE, and most well-known among them is the Edwin Smith Papyrus, shown in Figure 1 (Allen, 2005).



Source: photograph by Jeff Dahl, distributed under a CC-BY 2.0 license.

Figure 1: Edwin Smith Papyrus

The Edwin Smith Papyrus covered 48 medical cases including various injuries and wounds, including detailed anatomical descriptions and treatment (Porter, 1999). The Edwin Smith Papyrus is unlike other medical papyri of the time, such as the George Ebers or London Medical Papyri, in that it presents the medical information in a rational and scientific context, rather than through magic or supernatural phenomena (Ghalioungui, 1963).

The anatomists of Egypt furthered the knowledge of the human body substantially, and the knowledge passed to other civilizations of the world, and in particular to Greek scholars. One such researcher was Hippocrates, who was heralded as the “Father of Medicine” and attributed with the Hippocratic oath, which sets forth an ethical guideline for all physicians to follow (Boylan, 2005). Other Greek researchers added to the knowledge base, including Erasistratus, Herophilus, and Aristotle (Duckworth, Lyons, & Towers, 1962). Notably, Aristotle was the first to use the term “anatome”, which is a Greek word meaning “cutting up or taking apart” (Siddiquey, Husain, & Laila, 2009), although he focused primary on biology rather than the study of the human body. Arguably, the most influential Greek medical researcher was Galen. Galen was first to demonstrate the larynx creating vocal sounds and to recognize the difference between venous and arterial blood based on coloration (Nutton, 1984).

Rivaling these contributions, Ibn-Sina created the extensive medical works entitled the Canons. Within these encyclopedic tomes, he synthesized knowledge including general medicine, pharmacology, and extensive pathology. Specifically relating to anatomy, he discovered all the subcomponents of the eye and the functioning of the aortic valve. He also was the first to determine that muscle movements were the result of the nerves connected to them. His contributions to anatomical sciences were long lasting, with the Canons being used in teaching for hundreds of years (Virk, 2014). Demonstrating his lasting impact on medicine, the primary hospital in

Baghdad, Iraq is the Ibn Sina hospital, used by the United States Armed Forces as Combat Support hospital from 2003 until 2009 (Associated-Press, 2009).

Until this time, anatomy education was primarily done through mentorship, individual discovery, or isolated centers of education. For example, Hippocrates trained at the Asclepeion on Kos, and Galen trained at the Asclepion in Pergemon (Hatzivassiliou, 1997). Unfortunately, teaching anatomy in this fashion led to a great deal of knowledge fragmentation. During the 17^{th} and 18^{th} centuries, the science of anatomy rapidly advanced, and anatomy education began formalization. A number of factors contributed to this, primarily the introduction of the printing press (McLuhan, 2011). The printing press allowed mass reproduction of anatomical content that could be easily disseminated.

One popular educational format that emerged during this time was the anatomical theater. The anatomical theater was a large room, typically circular, with a table in the center for dissection of cadavers and animals (Castiglione, 1941; Winkler, 1993). Students were able to view the dissection from seats around the room, with a professional anatomist or physician performing a dissection and instructing on the related anatomy and physiology (Figure 2). With the standardization of curriculum and the wide spread use of anatomical theaters, the study of anatomy became relatively stable, with limited research. Soon, the modern age of anatomical education would began as a result of technology advancement, including computers and powerful microscopes providing new perspectives into molecular and cellular processes (Wong & Tay, 2005).

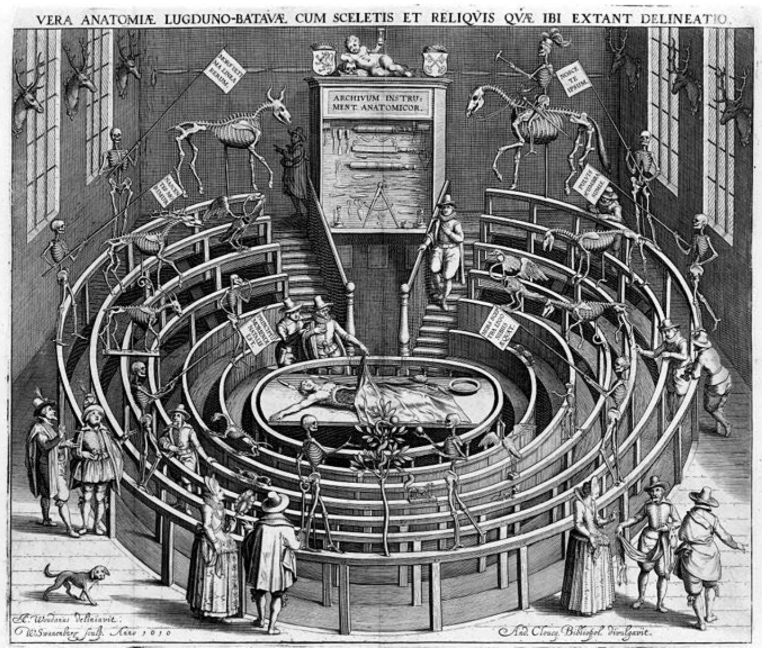


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Figure 2: Anatomical Theater

Current Medical Education

The current state of medical education evolved substantially due to technology advances, changes in curriculum, and time and budgetary constraints. To begin, the didactic, or lecture-based, portion of anatomy training changed as more and more information became available regarding cellular processes. These processes are important, especially related to drug and treatment interaction, and were subsequently included medical education. However, to allow time for teaching this information, anatomy courses were shortened, from a year and a half or two years to a single year (Wong & Tay, 2005). The truncation of these anatomy courses provides a challenge to instructors, to fit a year and half of anatomical information into a year or less.

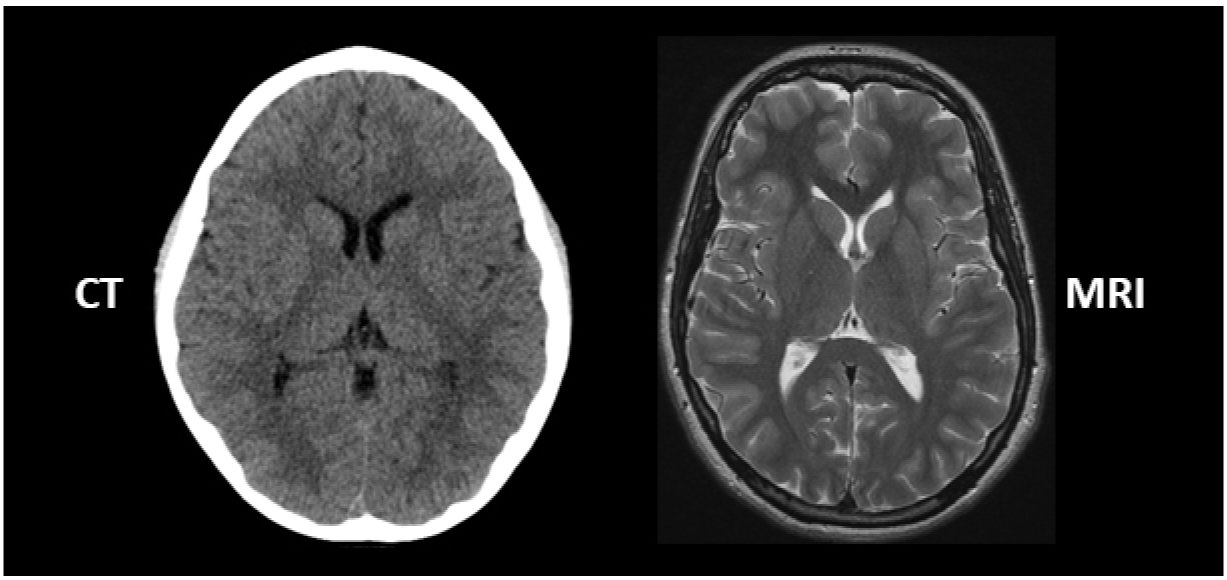
Anatomists also refined training techniques and processes. The anatomical theater, so widespread for hundreds of years, has been largely replaced by cadaver dissection laboratories

(Siddiquey et al., 2009). These laboratories provide students hands-on dissection access, allowing for individuals to learn at their own pace and to independently study anatomical structures in more detail. However, a small subset of medical schools have chosen to retain the anatomical theater approach in order to save money and provide a more structured learning format (McLachlan, Bligh, Bradley, & Searle, 2004). In a lower cost alternative to cadavers, physical models may be used to augment training, providing a 3D view and tactile experience. Physical models allow for viewing of surface anatomy and a limited amount of interactivity, through the removal of pieces / parts (Figure 3). The physical, hands-on, portion of anatomy education has become highly prevalent in anatomy training, either through cadaver dissection, physical model study, or a combination of teaching aids.

Source: Industrial Anatomy, https://industrialanatomy.wordpress.com/

Figure 3: Physical Anatomical Model

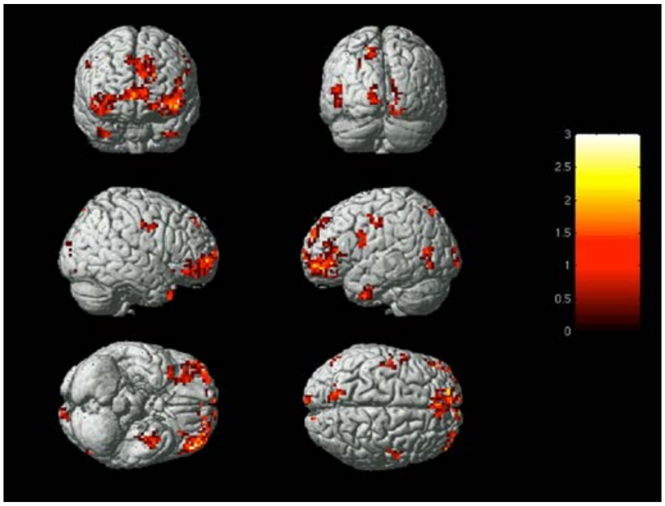
Technology advancement in medical imaging allowed for very detailed and high fidelity visualization of anatomy and physiology. A variety of medical imaging techniques exist for anatomical study, including magnetic resonance imaging (MRI) and computed tomography (CT). Magnetic resonance imaging uses a strong, uniform magnetic field and radio waves to create images of anatomical structures and pathologies. By detecting the signals emitted by excited hydrogen atoms, the MRI technique is able to determine changes in water concentration, and thereby determine different tissue variants. CT scanning takes a series of X-rays by rotating around 360º of the body. CT scanning uses a computer to combine the X-rays into a high resolution image of anatomy and pathology (Bushberg & Boone, 2011). In general, MRI scans give superior resolution for soft tissue imaging, while CT scans give better results for skeletal imaging (Figure 4).



Source: Alexander Towbin, https://blog.cincinnatichildrens.org/radiology/

Figure 4: CT (Left) and MRI (Right) Images of Transverse Slice of the Brain

Functional imaging can be used to tie these anatomical visualizations to physiological function, such as functional MRI (fMRI) or fluoroscopy. fMRI is primarily used to detect changes in brain activity and correlate these with anatomical structures. fMRI uses MRI techniques to image the anatomical structures, combined with the ability to detect blood oxygenation. As sections of the brain increase in activity, blood flow and oxygenation change allowing the fMRI to overlay the activity upon the MRI image of the brain (Jezzard, Matthews, & Smith, 2001) (Figure 5).



Source: (Kassam, Markey, Cherkassky, Loewenstein, & Just, 2013)

Figure 5: fMRI Image of Human Brain Activity

Fluoroscopy works in a similar fashion. Fluoroscopy places a patient between a fluorescent screen and an X-ray emitter. This technique allows real-time imaging of internal structures, and is commonly used for gastrointestinal diagnoses and orthopedic surgeries (Figure 6) (FDA, 2014). Combined with other imaging modalities, physicians and students now can visualize the anatomy and physiology of a patient.

Source: (Ranschaert, 2010)

Figure 6: Fluoroscopy of Barium Swallowing

The largest change in medical education results from the implementation of the personal computer within medical education. The ability to access medical content quickly in a variety of formats has completely changed the landscape of anatomical learning. Students have the ability to view photographs, illustrations, videos, anatomical models, medical imaging, and patient cases on demand. The large quantity of content combined with the ease of access and low cost has made personal computers a pivotal component in anatomical education.

Modern anatomy training still serves a vital role in medical education, providing the foundation necessary for understanding physiology, pathologies, and treatments. Numerous technologies and processes have enabled anatomy to be learned more efficiently, including medical imaging, personal computers, and cadaver dissections. However, a number of issues pose significant problems to anatomy education, and must be addressed through intelligent change and additional technological improvements.

Challenges in Contemporary Anatomy Education

Contemporary anatomy education has many challenges, as touched upon earlier, but additional detail is necessary to fully understand the problem space. To begin, learning anatomy is an exceptionally difficult task. The naming convention for many anatomical structures is based upon Latin or Greek languages and has been translated to modern English or British. Unfortunately, these translations are not uniformly done; as a result, there are a number of nomenclature variations across the healthcare community (Gest, Burkel, & Cortright, 2009). Additionally, the language bases many times result in terminologies that have little resemblance to our day-to-day vernacular. As a result, anatomical nomenclature seems very foreign to incoming students (Rector, 1999). Further, the scope of anatomical nomenclature is comprehensive of the body, meaning the problem space is huge (Kachlik, Baca, Bozdechova, Cech, & Musil, 2008). These factors combined demonstrate why learning only the proper terminology to identify anatomy is a challenge.

The challenge of learning the nomenclature is exacerbated when tied to spatial relationships. The names of anatomical structures are important, but in order to understand anatomy, the location, size, and orientation of the structure is equally important. The relationship of form and function is a key to learning medicine. For example, understanding where arteries and nerves lie is vital to knowing where and how deep to make an incision during surgery. Furthermore, the spatial relationship of a ligament to a bone is important when diagnosing many injuries, such as determining the correct ligament injured during a knee sprain. These situations highlight the urgent need to understand the spatial relationships, connections, and interdependencies within the human body. These spatial relationships are very difficult to learn, and many times rely on a student's innate visual-spatial ability. Garg et al. (1999), conducted a series of experiments to study how medical students learned spatial anatomy. The studies found students with high visual spatial ability (VSA) performed better using key views of anatomical structures. These findings were reinforced with a second study conducted by Garg, Norman, and Sperotable (2001) using 146 first-year students, which found spatial ability played a critical role in anatomical education. In a later study focusing more on the difficulty of spatial anatomy, Pandey and Zimitat (2007) conducted a survey of first-year medical students at an Australian university. These students reported learning anatomy and the spatial knowledge associated with anatomy as "hard work". Additionally, the study found that it was important for students to combine memorization, understanding, and visualization strategies to learn anatomy.

The struggle of anatomy students to learn anatomy has been demonstrated and discussed thoroughly in the literature. In the Netherlands, Maastricht University conducted two experiments studying student perceptions of anatomical education. In 1997, Van Mameran et al. (1997), reported that clinical residents felt a need for additional anatomical understanding before and during residency. Later, Drukker et al. (1999), reported that post-graduate medical students felt they lacked sufficient knowledge in gross anatomy. Prince et al. (2000) focused on the problem at the undergraduate level, and found that students were deficient in basic science knowledge, particularly in anatomy. Additionally, these students had issues translating their theoretical anatomical knowledge to clinical practice. Looking even further at this problem, Prince et al. (2003) sought to determine if problem-based learning approaches were a factor in student's poor perception of their anatomical knowledge. The group reported that both traditional learning approaches and newer problem-based learning curricula both resulted in poor student perceptions of anatomical knowledge. A great deal of this work was synthesized by Bergman et al. (2008), which came to the conclusion that nearly all students were insecure in their anatomical knowledge. More recent studies indicate that the problem still persists. Fitzgerald et al. (2008) sought the opinion of newly qualified doctors and found that nearly half the respondents felt they had insufficient anatomical education for their chosen specialties. The group tied this to the feeling to the decline in time spent learning anatomy. In a 3 year study, Bhangu et al. (2010) used Likert scale surveys to determine attitudes towards anatomy education during the 2nd year of medical school, and then again during the final year. The group reported that only 28% of 2nd year medical students and 31% of final year medical students felt their anatomy prepared them to interpret medical imagery. Worse still, only 14% of final year medical students felt confident in their overall understanding of anatomy. In an attempt to create an objective metric of anatomical understanding, Gupta, Morgan, Singh, and Ellis (2008) generated a test covering 15 areas of anatomical knowledge, including the anatomy of clinical examinations of the heart, chest, and nervous system; interpretation of radiographs; anatomy of common fractures; and anatomy of clinical procedures. The test was administered to junior doctors and a range of more senior level doctors. The disparity was significant, with junior doctors scoring substantially lower. The authors concluded that additional attention should be given to anatomy education. The literature from the past 15 years is consistent: students believe they are lacking in anatomy education, and in some cases, have been objectively shown to be deficient.

In addition to the student's perceived difficulty in learning anatomy, instructors have similar perceptions. Cottam (1999) conducted a study to determine the attitude of residency directors about incoming residents. The study reported that the majority (57%) of residency directors felt incoming medical residents needed a refresher in anatomy training. Waterson and Steward (2005) conducted a survey that found a majority of clinicians felt that anatomy teaching time was inadequate. Even more compelling, these clinicians felt that the deficiency in anatomical knowledge was significant enough to place knowledge below the minimum level for providing safe patient care. Lazarus, Chinchilli, Leong, and Koffman (2012) conducted a study gathering the perceptions of students, clinicians, and academic anatomists at the same time. The study found that medical students and clinicians felt that the students had difficulty translating their anatomical knowledge to the clinical setting and patient care. The authors feel this "suggests that while some anatomical learning, either through review or application, is taking place during clinical rotations this education is not to the degree and/or scope required for a successful clinical practice". The combination of instructor and student perception that students are deficient in anatomy knowledge gives credence to the scope and severity of the problem.

Until this point, the issues in contemporary anatomical education have been focused on typical civilian medical education. Military medical education experiences similar issues. The Uniformed Services University for Health Sciences (USUHS) trains many of the physicians in the Armed Services, and faces the same challenges as other medical schools. However, military medical training also encounters certain unique issues. To begin, casual conversations with confidential Navy physicians and medical trainers who work in JPC-1, a joint steering and funding committee for military medical simulation, indicate that military medical training does not always take place in a traditional educational setting. Refresher training for anatomy and procedures requiring anatomical understanding may occur in austere conditions. For example, these confidential experts and trainers indicate that the Navy may conduct shipboard refresher training during deployments. In such scenarios, the space is constrained, meaning anatomical aids such as cadaver labs or cadaver display tables are not feasible. Another user group experiencing austere training conditions is the Special Forces Medics. This group many times will have minimal infrastructure to train, including minimal power and limited or no internet connectivity. In such a case, lower-power education adjuncts would be needed to help train.

Within both the military and civilian sectors, medical education comprises a key role. Anatomical education serves as a key foundational piece to that education, but faces many challenging issues. Decreased teaching time, difficult subject matter, and complex spatial relationships all combine to create a difficult subject that students and teachers feel is not being conveyed adequately.

3D Visualization Technology – A Potential Part of the Solution

The inherent difficulty of anatomy combined with current challenges, including truncation of teaching time and the inclusion of large quantities of new information, has created a difficult environment within anatomy education. In 2014, Yammine (2014) reviewed the current state of anatomy, and found the study of anatomy was in a steady state of decline at the undergraduate and graduate level. One of the author's suggestions was an evaluation of 3D visualization technologies to augment anatomy education. Within this dissertation, a new 3D visualization training adjunct, holography, will be utilized with the goal of improving spatial understanding of anatomical structures. 3D visualization, as used in this dissertation, focuses on "the visualization of three-dimensional phenomena (architectural, meteorological, medical, biological, etc.), where the emphasis is on realistic renderings of volumes, surfaces, illumination sources, and so forth" (Friendly & Denis, 2012). 3D visualization has the potential for improving student performance and spatial understanding, while reducing cognitive load. Cognitive load refers to the total amount of mental effort being used for a task (J Sweller, 1994). This dissertation will continue with chapter 2 presenting a thorough literature review covering 3D technologies used to visualize anatomy, and the assessment of those technologies. Chapter 3 covers experimental design, including the instruments for data collection and the proposed data analysis techniques. Chapters 4 and 5 present the results of the experiment, and the conclusions drawn.

CHAPTER 2: LITERATURE REVIEW

Visualization is “the act or process of interpreting in visual terms or of putting into visible form” ("Visualization," 2015). More specifically, visualization “represents a support technology that enables scientists and engineers to understand complex relationships typically represented by large amounts of data” (Lang, Kieferle, & Wössner, 2003). While the focus of this dissertation is on the display hardware used during visualization, it should be noted that a large subset of the research in visualization focuses on the software needed to assemble and analyze large quantities of data and generate a representation that humans can more easily comprehend. Within medical visualization, the tasks handled by software include image reading, sampling, segmentation, volume rendering, and surface display (Starreveld, Gobbi, Finnis, & Peters, 2001). A recent review paper by Botha et al. (2014) discusses the advances in medical visualization during the past 30 years and includes discussion of the current challenges and future directions in the field, including advances in data acquisition, mobile display technologies, illustrative visualizations in medicine, and hyper-realism.

The aforementioned software tools are necessary to generate the representation of a medical data set, but without a display hardware component, the user gains no further insight into the data. The display component generates the visible light for the human visual system to process. Historically, the use of cathode ray tube (CRT) monitors was the primary display modality. More recent techniques focus on a flat screen, including liquid crystal displays (LCD), plasma display panels (PDP), light emitting diodes (LED), and organic light emitting diodes (OLED). Castellano reviewed these displays and the techniques used to create them thoroughly (Castellano, 2012). However, basic versions of these displays only physically provide the horizontal and vertical dimensions, and must rely on alternative means to provide the third dimension of spatial perception – visible depth.

Three dimensional displays have the potential to be a valuable tool in medical visualization by providing visible depth in a more comprehensive fashion. The human visual system is able to perceive depth using a combination of monocular and binocular depth cues. Before further discussing 3D displays, a brief primer on the human visual system and depth cues is presented.

Human Visual System

The human visual system has evolved to allow for 3D perception through a series of optical improvements. Rods and cones, or photoreceptors, in the retina allow for color perception, of up to 10 million color distinctions. Extra-ocular muscles allow for the motion of the eye for a wide field of view. A complex lens with attached musculature allows for focusing at a variety of scales and distances. These, combined with a host of other anatomical features, have enabled the human eye to provide spectacular vision capability (Montomery, 2014).

The human visual system uses the eye as the detector, and the brain as the processing unit. The brain receives the nervous signals from the eye and processes the incoming scene. To perceive a scene in three dimensions, the human visual system uses a variety of cues to determine the depth of objects within the scene. These depth cues are generally split into two categories: monocular, sometimes referred to as pictorial, depth cues, requiring only a single eye; and binocular depth cues, requiring the input of both eyes. These depth cues are summarized below (Table 2).

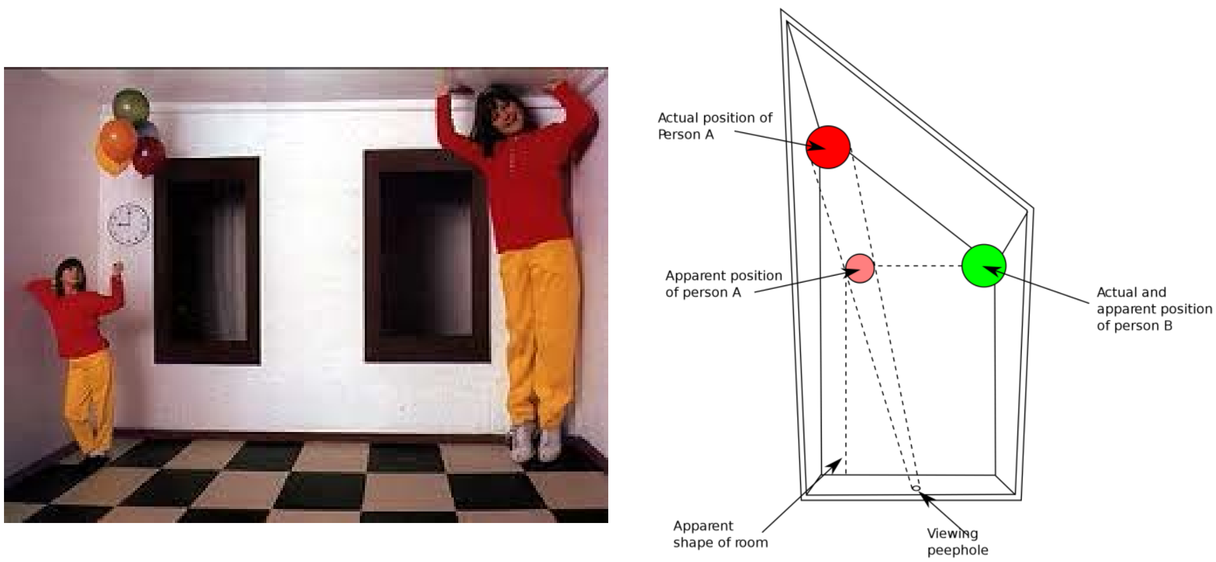
Table 2: Monocular and Binocular Depth Cues

Cue	Category	Definition
Retinal Image Size	Monocular	When the real size of the object is known, our brain compares the sensed size of the object to this real size, and thus acquires information about the distance of the object.
Texture Gradient	Monocular	The closer we are to an object the more detail we can see of its surface texture. So objects with smooth textures are usually interpreted being farther away.
Motion Parallax	Monocular	The effect whereby the position or direction of an object appears to differ when viewed from different positions. The motion of the viewer produces motion parallax.
Kinetic Depth Effect	Monocular	The effect whereby the three-dimensional structural form of an object can be perceived when the object is moving
Linear Perspective	Monocular	A type of monocular cue in which parallel lines appear to converge at some point in the distance.
Overlap	Monocular	When objects block each other out of our sight, we know that the object that blocks the other one is closer to us.
Lighting and Shading	Monocular	When the location of a light source is known and objects casting shadows on other objects, we know that the object shadowing the other is closer to the light source.
Accommodation	Monocular	Accommodation is the tension of the muscle that changes the focal length of the lens of eye.
Convergence	Binocular	A binocular cue based on signal sent from muscles that turn the eyes. To focus on near or approaching objects, these muscles turn the eyes inward. The brain uses the signal sent by these muscles to determine the distance of the object.
Stereopsis	Binocular	The perception of depth produced by the reception in the brain of visual stimuli from both eyes in combination.

Source: (Hackett & Fefferman, 2014; Kalloniatis & Luu, 2007; Teittinen, 2014)

By understanding the mechanisms employed in the human visual system, the potential benefits of 3D displays become more apparent. Monocular depth cues only give a piece of the puzzle, and the human visual can be easily confused without the addition of binocular depth cues. One of the most famous examples that demonstrates this confusion is known as Ame’s Room. Ame’s Room presents a viewer with a monocular view of a specially designed trapezoidal room

(Ames Jr, 1951). The viewer perceives that the person on the right is a much larger in size that the person on the left; when in fact the room is shaped to take advantage of monocular cues such as retinal image size (Figure 7). Binocular cues such as convergence and stereopsis, or the addition of motion parallax, would overcome the confusion of this illusion and give the viewer the appropriate depth perception.



Source: Alex Valavanis, https://commons.wikimedia.org/wiki/File:Ames_room.svg

Figure 7: Ames' Room

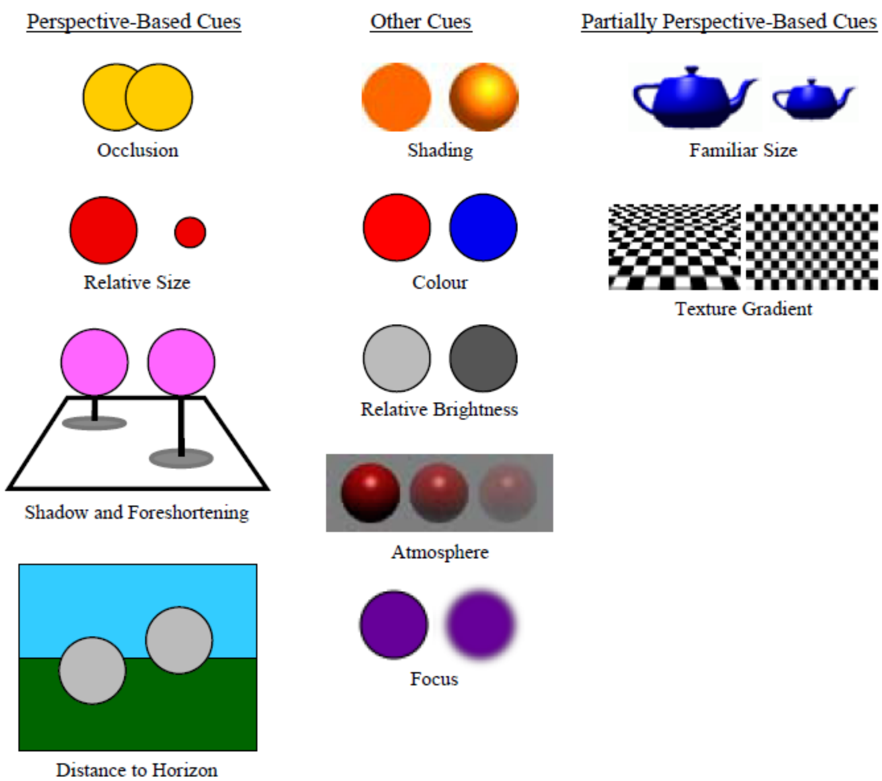
From the example above, binocular and parallax depth cues are important components to accurately understanding a 3D scene. Since traditional 2D displays are unable to generate these cues, 3D display modalities have become more widespread. The implementation of 3D visualization has increased for a variety of purposes, including medicine, geography, engineering, human-computer interaction, and spatial understanding tasks. The visualization of three-dimensional representations has demonstrated considerable advantages in a variety of areas and tasks, ranging from generalized spatial knowledge acquisition to in-depth medical procedures. A review by Geng (2013) broadly split displays into three categories: traditional 2D displays; stereoscopic 3D displays requiring special glasses; and autostereoscopic 3D displays not requiring glasses. This review is organized using these categories, and adds a category for augmented reality. This chapter covers the techniques and technology used to achieve 3D visualizations, studies demonstrating 3D display technology in anatomical education, and studies assessing the effect of 3D visualization in anatomical education.

Techniques and Technology for 3D Visualization

Researchers use the visual system as the starting point to create a 3D visualization. The basic principle is the same for nearly all 3D display technology: each individual eye must be presented with a unique view of an object in a positionally correct fashion. In doing this, researchers allow the visual system to take over and process the object in a similar manner to physical objects. For many years, researchers have achieved this through a variety of clever mechanisms, which each have strengths and weaknesses regarding the nature of 3D visualization they provide. Within this literature review, the technologies and techniques used in 3D visualization for anatomical content will be covered using Geng's categorization, including monoscopic 3D, stereoscopic 3D, autostereoscopic 3D, augmented reality visualizations, and finally holography.

Monoscopic 3D

The most fundamental method to achieve a base level of 3D spatial perception of an anatomical model is through monocular depth cues. Computer graphics replicate these depth cues, including image attributes such as interposition, occlusion, size, shading, surface texture gradients, atmospheric effects, and brightness (Pfautz, 2000; Sherman & Craig, 2002). Pfautz gave a series of examples within a thesis, outlining simplistic representation of monoscopic depth cues using computer graphics (Figure 8). Monocular-based spatial reasoning is occasionally referred to as "2.5D" (Van Dam & Feiner, 2014), but within this article the more precise term of monoscopic spatial reasoning, or monoscopic 3D is used in place of more ambiguous terms such as "2.5D" or "pseudo-3D". Two additional depth cues can be added to traditional monoscopic 3D displays, which are parallax and the kinetic depth effect.

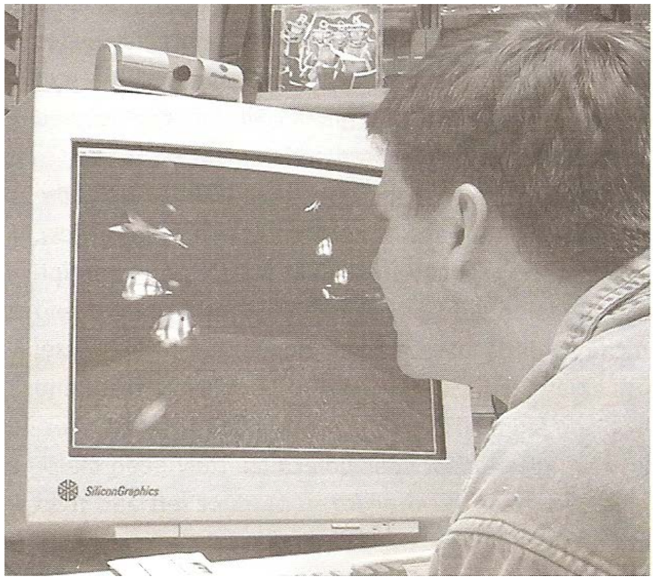


Source: (Pfautz, 2000)

Figure 8: Monoscopic Depth Cues in Static Computer Graphics

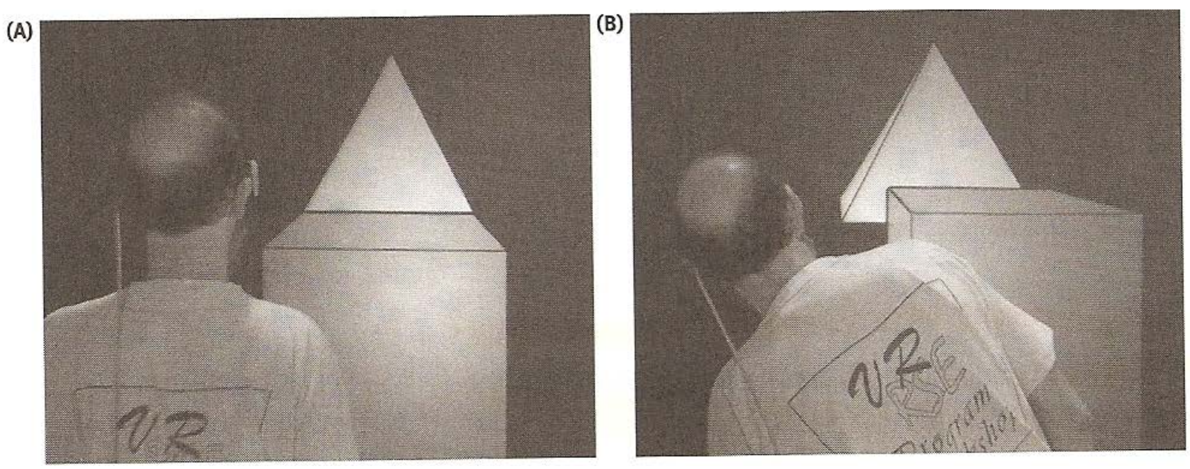
Parallax Display

Parallax is a depth cue that may be obtained in computer visualization through motion of the viewer. Using head tracking, such as "fishtank 3D" shown in Figure 9 or HMD tracking show in Figure 10, the perception of the depth of an object may be viewed by tracking the relative motion of the user and displaying the changed viewpoint of the world.



Source: (Sherman & Craig, 2003, pg 140)

Figure **9: Fishtank VR with Head Tracking Camera**



Source: (Sherman & Craig, 2003, pg 120)

Figure 10: Depth Cue from Viewer Motion

Kinetic Depth Effect

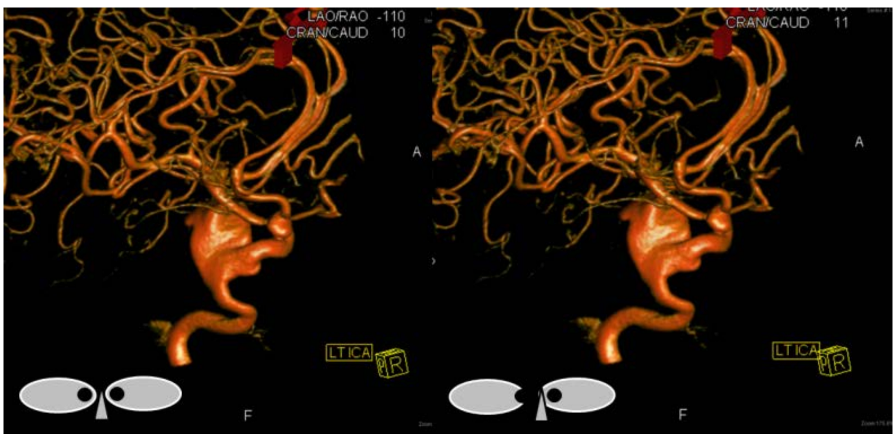
The kinetic depth effect refers to the ability to perceive the three-dimensional structural form of an object when the object is moving (Wallach & O'connell, 1953). The amount of depth perception is based on the number and amount of angular and/or translational displacement degrees of freedom afforded the object in motion. Motion, primarily rotation, may be through automatic movement of a 3D object or through user interaction, such as via touch screen or mouse. Quality of depth perception depends on the object fidelity given translation closer to or further away from the viewer. The Spinning Dancer is an example of kinetic depth effect in an illusion with few other depth cues, shown in Figure 11.

Source: Nobuyuki Kayahara, https://commons.wikimedia.org/wiki/File:Spinning_Dancer.gif

Figure 11: Kinetic Depth Effect Present in the Spinning Dancer Illusion

Stereoscopic 3D displays

Stereoscopic 3D display involves multiplexing two different views of an image to the viewer, in what are commonly known as "stereo pairs", and requires the viewer to wear glasses (McIntire, Havig, & Geiselman, 2012) (Figure 12). Multiplexing techniques deliver the stereo pairs spatially or temporally interlaced. Spatial interlacing technologies use 3D glasses with passive color anaglyph lenses or polarization interlaced lenses to filter the stereo pairs (Sherman & Craig, 2003). Time-multiplexed technology interlaces the stereo pairs by rapidly shuttering lens for each eye. Shuttering presents a rendered image to the left eye, while blocking the view of the right eye, then presenting a rendered image to the right eye while blocking the left (Geng, 2013). Through these methods, stereoscopic displays provide all the cues present in monoscopic 3D, while adding binocular depth cues, such as stereopsis.



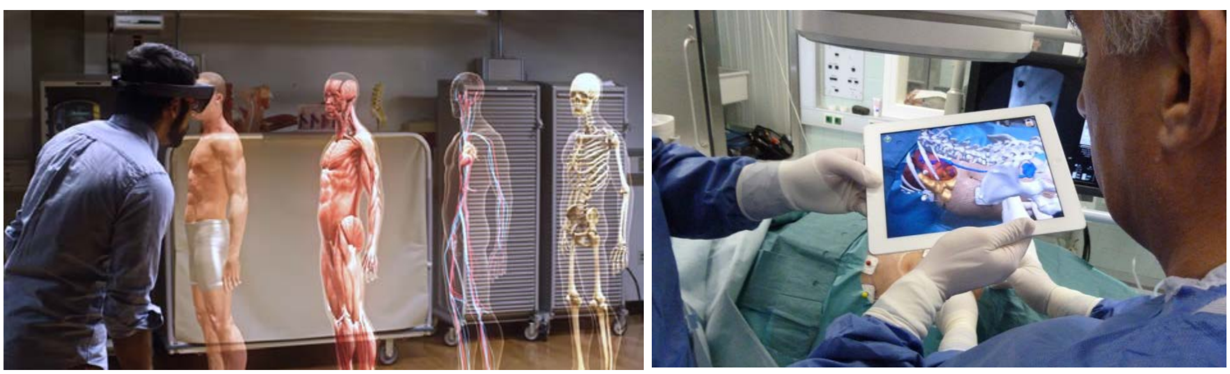
Source: www.neuroangio.org

Figure 12: Stereo Pairs of Anterior Cerebral Artery

Stereoscopic 3D displays encounter certain issues, particularly with head mounted displays (HMDs). In stereoscopic displays, convergence accommodation conflict occurs when focus cues, namely accommodation and blur, specify the depth of the display rather than the depth of the image. In other words, the eyes focus on the depth of the display which conflicts with the depth of the presented image (Inoue & Ohzu, 1997). This conflict can result in visual fatigue, and in some cases, significant discomfort (Kooi & Toet, 2004). Specific to HMDs, there is the discomfort of wearing the physical device, which grows over time and with devices that are heavier.

Augmented and mixed reality displays

Augmented reality and mixed reality are hybrid techniques that overlay digital information on real world objects to enhance the user experience (Berryman, 2012). As an example, the Microsoft HoloLens or the Magic Leap "overlays 3D images on the real world, such as a 'hologram' of a tiny building that appears to be sitting on a coffee table that's really in front of you" (McCracken, 2015). For anatomy, this may be an overlay onto a live human, a medical mannequin, or a physical model. Augmented reality uses a video or optical see-through HMD, or a mobile display technology, to achieve the superimposed visuals (Figure 13). Issues with registration of the augmented visuals and poor visibility in bright environments, such as direct sunlight, continue to challenge augmented reality displays.

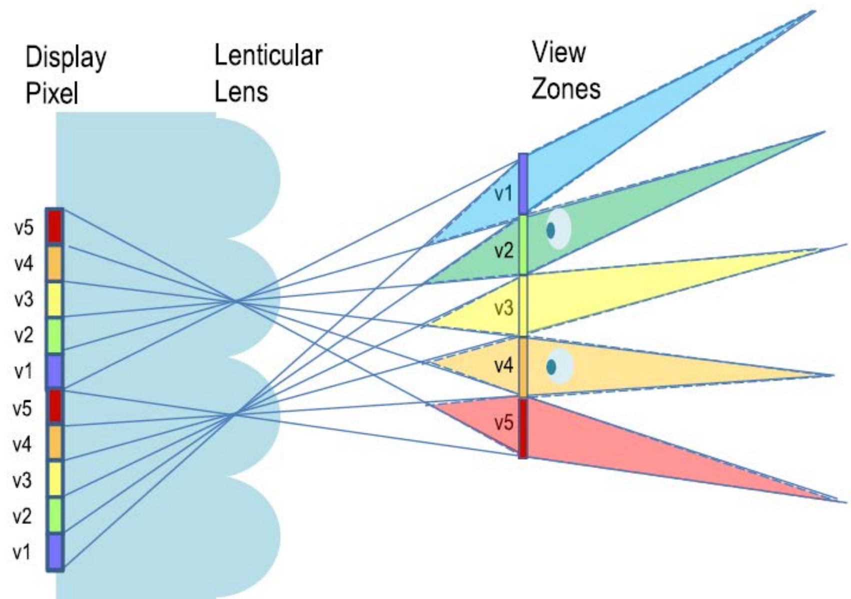


Source: Microsoft Hololens: https://www.youtube.com/watch?v=SKpKlh1-en0

Figure 13: Augmented Reality via Optical See-Through HMD (Left) and Video See-Through (Right)

Auto-stereoscopic displays

Auto-stereoscopic visualization presents a 3D image to the viewer, including both monocular and binocular depth cues, without the aid of glasses or HMDs (Dodgson, 2005). Dodgson categorized autostereoscopic displays as either multi-view displays or volumetric displays. Multi-view display technologies use a barrier or film applied to the display surface, such as lenticular lens or parallax barrier. Lenticular lens employs a series of flat-cylindrical lenses placed across the image plane to create an auto-stereoscopic image (Hong et al., 2011). The lenses are aligned with the vertical pixel columns, and a set number of pixel columns are assigned to a single view. The role of a lenticular lens is to magnify and transfer the information of specific pixels to the designated position. Therefore, observers in different viewpoints can watch different images, and binocular disparity, convergence, and motion parallax can be realized (Hong et al., 2011). An example of a 5-view lenticular lens display system is shown in Figure 14.



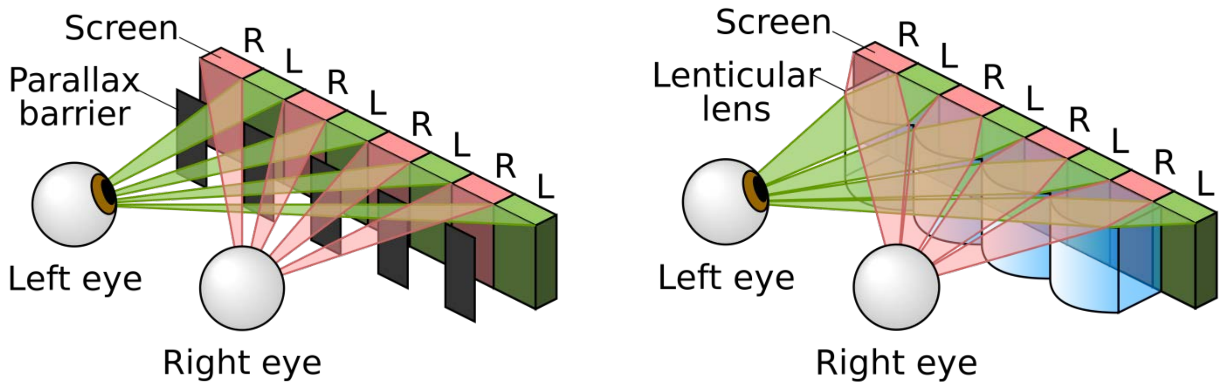
Source: (Geng, 2013)

Figure 14: 5-View Lenticular Lens Display

Understanding the functioning of the lenticular lens, it becomes clear that this technique has one significant advantage, principally the reuse of 2D fabrication processes (Geng, 2013). The lens can be applied after fabrication of the display, and potentially used to create a 3D display in an ad hoc fashion. However, lenticular lens has a number of challenges compared to other forms of autostereoscopic 3D.

1) A lenticular lens display has a limited number of views due to the width of the lenses, meaning the display only has a limited amount of horizontal parallax (Geng, 2013).
2) A lenticular display has limited resolution. The lenses cut the resolution of the full display by 1/N, where N is the number of views (Geng, 2013). As such, high-resolution autostereoscopic displays are very difficult to achieve with lenticular lens. Certain techniques can be used to overcome some of this issue, such as slanting the lenticular lenses (De Zwart, IJzerman, Dekker, & Wolter, 2004).
3) The lenticular lens modality allows for cross-talk and image flips. When one sees the view intended for another eye, the human visual system perceives the stereo effect incorrectly (Geng, 2013).
4) A lenticular lens lacks full parallax in the horizontal direction and provides no parallax in the vertical direction. If a user wishes to look fully around a 3D object, a lenticular lens cannot provide that effect. The 3D effect is only for a limited field of view and only in single direction.
5) Convergence accommodation conflict is present and can lead to visual fatigue, discomfort, and perceived distortion in 3D structure (D. M. Hoffman, Girshick, Akeley, & Banks, 2008).

A second common auto-stereoscopic technology is a parallax barrier. A parallax barrier is an opaque sheet of material with slits at regular intervals. If a viewer is positioned appropriately, the right eye view of the stereo pair will be visible only to the right eye, and the left eye will view the stereo view for the left eye (Halle, 2005). A parallax barrier and lenticular lens produce the same horizontal parallax only effect, and present an optically analogous 3D image (Geng, 2013). The techniques are illustrated side by side to show the similarity (Figure 15).

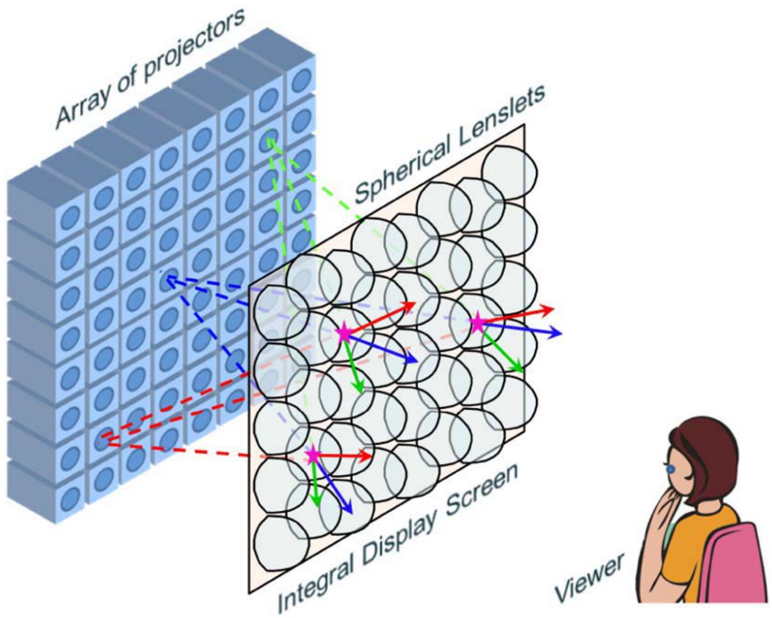


Source: (Geng, 2013)

Figure 15: Parallax Barrier (Left) and Lenticular Lens (Right)

Since the techniques are so similar, it follows that the challenges and advantages are also similar. A parallax barrier, just as a lenticular lens, can be applied onto a 2D display with proper alignment and sizing, allowing it to take advantage of existing displays and fabrication facility. All of the disadvantages of lenticular lens – limited views, limited resolution, cross-talk, image flip, horizontal parallax only, and convergence accommodation conflict – apply to parallax barriers. Parallax barriers have one additional significant challenge, which is brightness. The opaque material over the display blocks light, meaning only the light coming through the slits reaches the viewer. This results in significantly decreased brightness of the display (Geng, 2013).

Another form of auto-stereoscopic display is integral imaging. Integral imaging uses a similar technique to lenticular lens, except it uses circular lenslets rather than flat-cylindrical lenses (Martinez-Cuenca, Saavedra, Martinez-Corral, & Javidi, 2009). This allows integral imaging displays to achieve both horizontal and vertical parallax. Integral imaging also avoids the problem of convergence – accommodation conflict, which as mentioned prior can cause discomfort and visual fatigue (Xiao, Javidi, Martinez-Corral, & Stern, 2013). Figure 16 shows a visual representation of an integral-imaging based display using spherical lenses.



Source: (Geng, 2013)

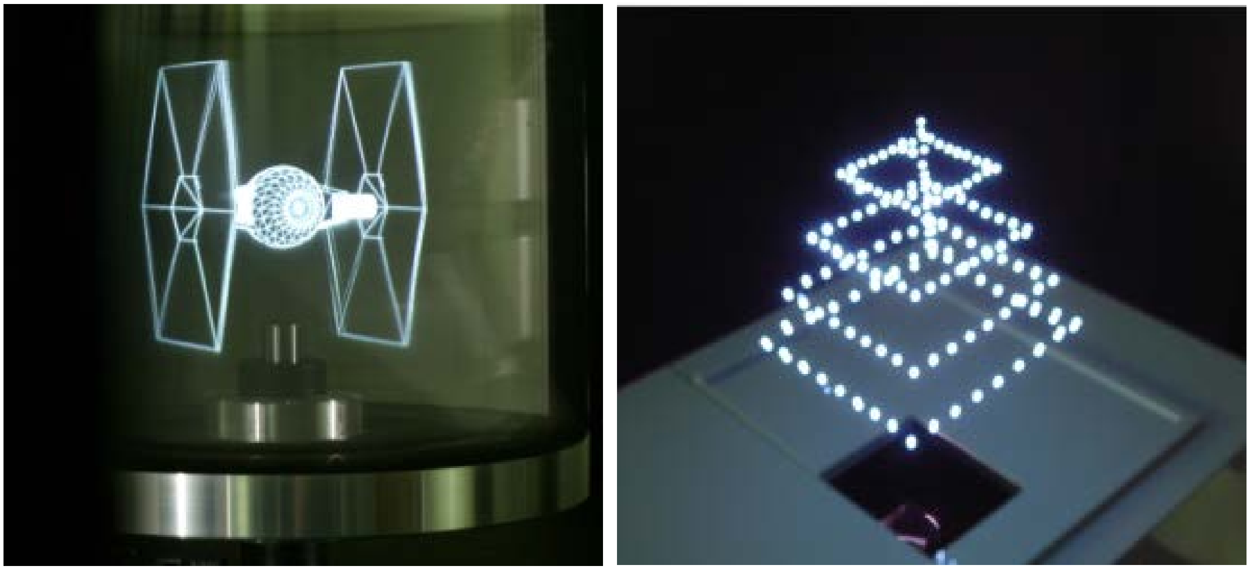
Figure 16: Autostereoscopic 3D Display using Integral Imaging

With integral imaging, resolution is an important consideration. Similar to lenticular lenses and parallax barriers, the resolution of the display is reduced by 1/N, N being the number of views. Because of the horizontal and vertical parallax of this display, that means the resolution is reduced in both directions, making the resolution a significant limiting factor. Additionally, Kim et al. report limitations in viewing angle and image depth range (Kim, Hong, & Lee, 2010).

The other category of auto-stereoscopic displays is volumetric displays. Volumetric displays project image points to definite loci in a physical volume of space where they appear either on a real surface, or in translucent (aerial) images forming a stack of distinct depth planes(Pastoor & Wöpking, 1997). Volumetric displays are generally classified into 3 categories: swept volume, static volumes, and holographic displays (Favalora, 2005). In swept volume displays, the image space is generated by mechanical motions of a display panel (either a 2D panel such as a mirror (Jones, McDowall, Yamada, Bolas, & Debevec, 2007) or a helix panel (Gately, Zhai, Yeary, Petrich, & Sawalha, 2011))(Figure 18). Swept volume displays have improved in recent years due to the implementation of LED light sources (Gately et al., 2011), open-source display architectures to drive down costs (Abraham, 2013), and general improvements in the optical design (Sun, Chang, Cai, & Liu, 2014). The main drawbacks to swept volume displays are:

1) Large number of moving parts
2) Limited scalability
3) Barrier between the observer and the image (Geng, 2013).

Static volume displays generate 3D imagery by coaxing a volume into emitting light in which the bulk properties remain static (Favalora, 2005). In these, a liquid, gas, or solid is excited by laser in a precise manner, causing the material to illuminate and generate a 3D image (Langhans, Guill, Rieper, Oltmann, & Bahr, 2003). Generally, these samples have to be enclosed and separated from the viewer, but a technique introduced by Cho et al. uses a pulsed laser to ignite molecules in the air and generate plasma light points, removing the need for a specialized volume of material (Cho, Bass, & Jenssen, 2007; Kimura, Uchiyama, & Yoshikawa, 2006) (Figure 17). Unfortunately, static volume displays are difficult to manufacture and many times represent safety risks to viewers due to the necessity for high-power lasers (Geng, 2013). Additionally, these are many times not in color, due to the material used within the static volume.



Source: (Jones et al., 2007; Kimura et al., 2006)

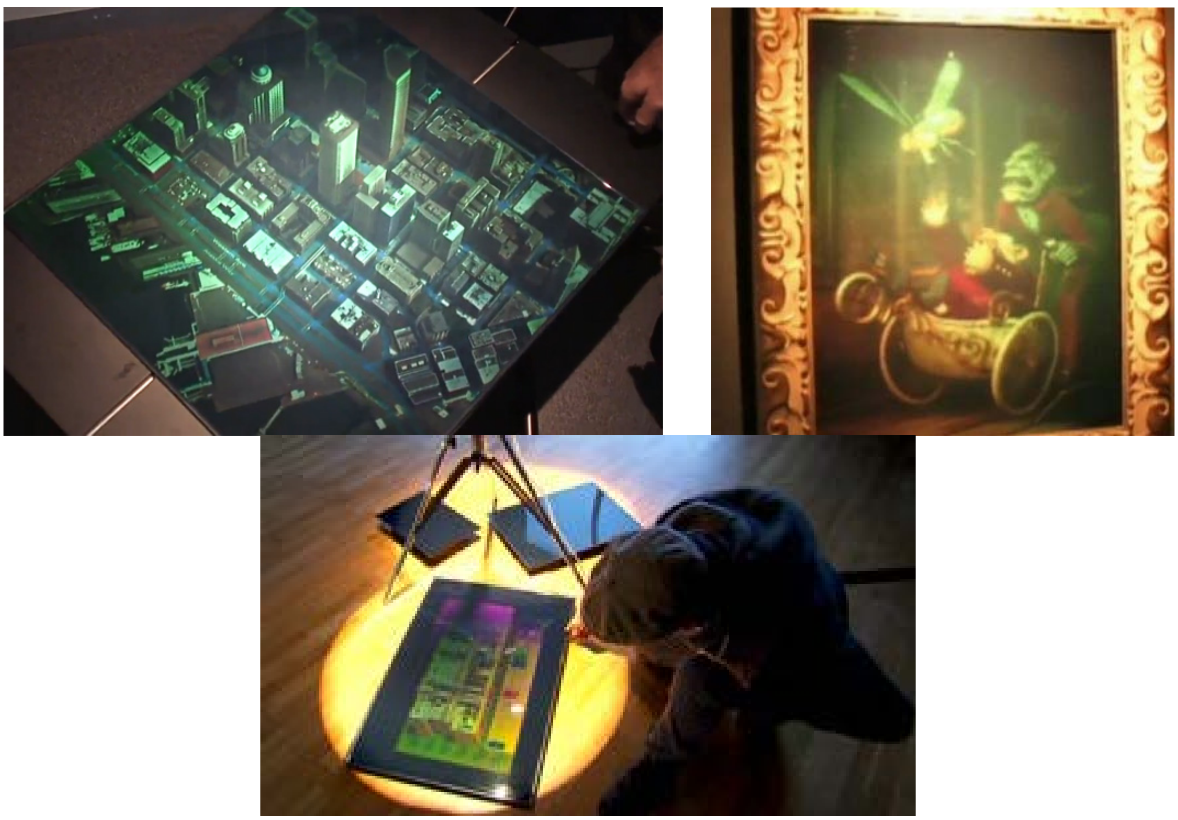
Figure 17: Swept Volume Display (Left) and Static Volume Ignited Plasma Display (Right)

<u>Holography</u>

The concept of holography has been around since 1947, when Dennis Gabor invented a new method for encoding and displaying 3D objects (Gabor, 1948). However, the technology was not sufficient to realize his theories, until 1960 when the white light laser became available. At this point, practical white light holography was achieved by Leith and Upatnieks (Leith & Upatnieks, 1962). Based on these principles, researchers have created a variety of holographic visualization technologies. Generally, holographic displays are split into two groups: computer generated holography to print holograms and computer generated electroholography (Geng, 2013).

Printed holograms are created in a process known as direct write digital holography (DWDH), wherein the holographic substrate is divided into a matrix of small holographic pixels ("hogels" or "holopixels"), each of which is recorded using a compact object and reference beam (Brotherton-Ratcliffe et al., 2011). Improving the print time, Klug et al., created a single step process to create large format full-color reflective holograms (Klug, Holzbach, & Ferdman, 2001).

The current generation of reflective holograms allows full color, autostereoscopic, fully-parallax visualizations of 3D objects on a print media. Print holograms are reflective displays, meaning that the light source must be external and directed at the surface of the hologram to view the 3D image. Lastly, these holograms have the significant drawback of being static; the image does not move. Examples of these holograms have been created by Zebra Imaging, RabbitHoles Media, and Holoxica (Figure 18).

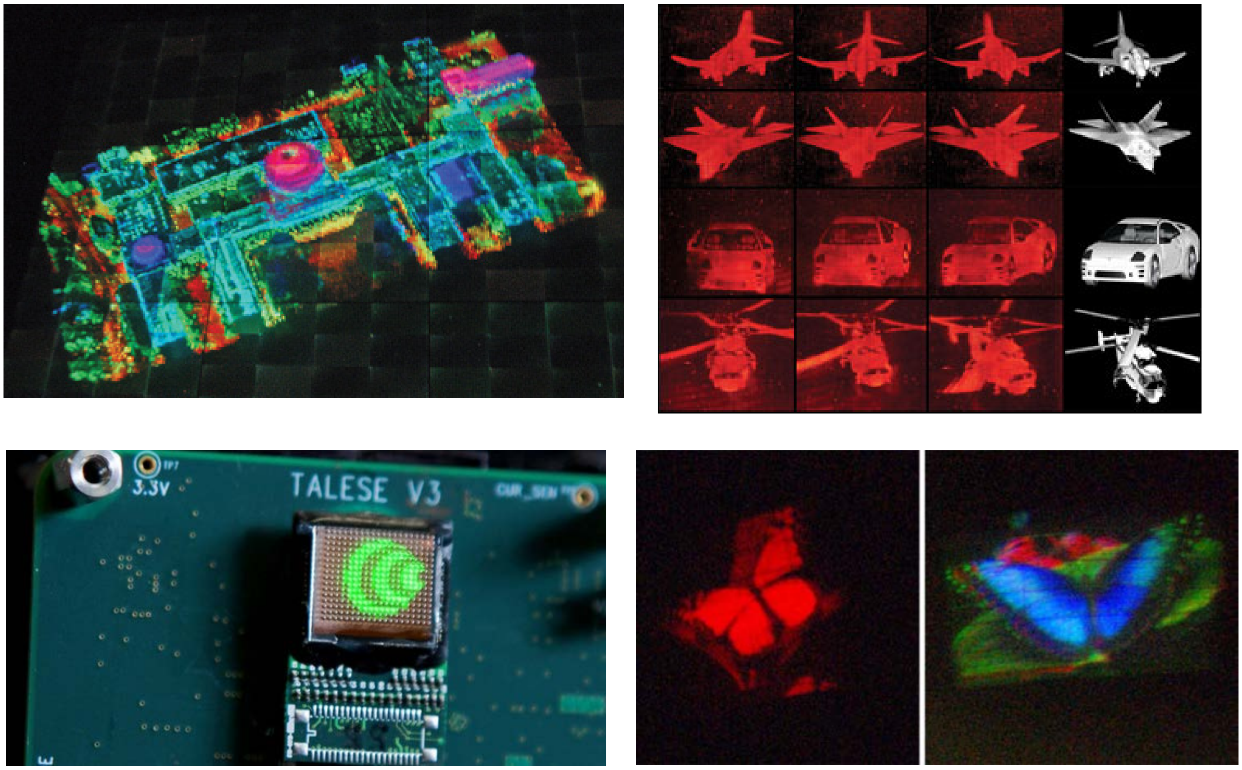


Source: Zebra Imaging (Top Left), RabbitHoles Media (Top Right), and Holoxica (Bottom)

Figure 18: Digital Holographic Prints

Computer generated electroholography is used to create dynamic holographic displays, meaning the display is capable of 3D motion. Current displays utilize spatial light modulators and advanced optical arrays to generate the holographic image (Reichelt et al., 2012). These displays are autostereoscopic, and have high degrees of parallax. Some displays have full 360º parallax, allowing users to stand at all angles around a display and collaborate (Klug et al., 2013). Holographic displays are not confined to a static volume or housed behind a panel, allowing closer and safer viewing than other volumetric displays. The Zebra zScape motion display (Klug et al., 2013), the Ostendo holographic display (Lewin, 2014), and the Holoxica holographic display (Khan, Can, Greenaway, & Underwood, 2013) are some current commercial offerings.

While holographic displays have been referred to as “the holy grail” of 3D display due to being autostereoscopic, fully parallax, light field display technology (Benton & Bove Jr, 2008), the displays current have a set of serious drawbacks. The first is resolution; in order to have a fully holographic display, a pixel pitch size of 1μm is required; this would lead to a reasonable screen size having pixels numbering in the trillions. This leads to issues in all areas of the technology, from data transmission, computation, visualization, and display optics (Geng, 2013). The current generation tries to overcome these issues with clever engineering, but the displays all have deficiencies in resolution, refresh rate, color consistency, brightness, uniformity, tiling, and scaling. Photographs of the current state of the art highlight these deficiencies (Figure 19).



Source: Zebra Imaging zScape (Top Left), University of Arizona (Top Right), Ostendo (Bottom Left), MIT Media Lab (Bottom Right)

Figure 19: State of the Art in Holographic Displays

Display technology summary

3D display technologies have strengths and weaknesses, summarized in Table 3. Educators and researchers should determine their operating environment and visualization needs, and make technology choices to best accommodate their use case. Display technology trends continue to progress to improve resolution, view angle, refresh rate, and cost. At present, monoscopic 3D and stereoscopic 3D are the most accessible due to cost and availability of technology. In the future, commercial investments in products such as HoloLens and Google Glass may drive augmented reality towards increased accessibility and lower cost. Holographic and other autostereoscopic displays represent the most capability and don't require glasses or an HMD, but are the least mature and subsequently least accessible at present.

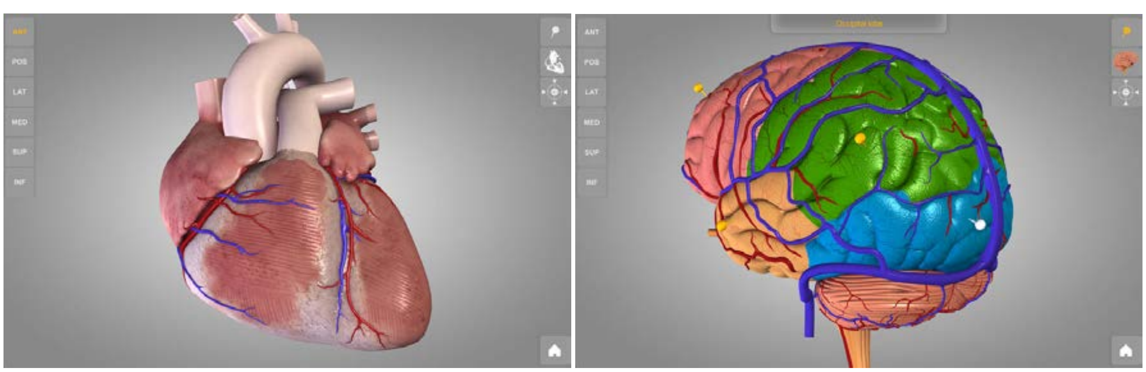
Table 3: Summary of Strengths and Weaknesses of 3D Display Technologies

Technology	Strengths	Weaknesses
Monoscopic Spatial Perception	- Utilizes traditional print media or low cost monitors - No special eye glasses required - High resolution - Commercially available in Black & White and various levels of Color	- No binocular depth cues - No parallax
Monoscopic Spatial Perception with Kinetic Depth Effect	- No special eye glasses required - High resolution - Commercially available - Object movement (e.g. innately propelled or user interaction) produces kinetic depth effect depth cue	- No binocular depth cues - Amount of depth perception based on the number / amount of angular and/or translational displacement degrees of freedom. Quality of depth perception depends on object fidelity at viewing distance.
Monoscopic Spatial Perception with Head Motion Parallax	- Head tracking device required but no special eye glasses required - High resolution - Commercially available - Parallax through movement of viewer	- No binocular depth cues - Amount of depth perception based by the number and amount of angular and/or translational displacement afforded the viewer by the display type
Color Anaglyph	- Utilizes traditional low cost screens - High resolution - Commercially available	- Skewed sense of color - Requires eye glasses - Convergence-Accommodation Conflict
Polarization Interlaced	- High resolution - Commercially available	- Requires expensive projectors - Requires eye glasses - Convergence-Accommodation Conflict
Time-Multiplexed	- High resolution - Commercially available	- Reduced brightness due to shuttering - Convergence-Accommodation Conflict
Augmented Reality	- High resolution - Highly immersive	- Expensive, man-worn equipment - Physical fatigue and potential for eye strain - Registration and occlusion issues
Lenticular Lens	- Autostereoscopic - Can be applied to existing displays	- Horizontal Parallax Only - Reduces resolution - Cross talk and image flip - Limited viewing angle
Parallax Barrier	- Autostereoscopic - Can be applied to existing displays	- Horizontal Parallax Only - Reduces resolution - Cross talk and image flip - Reduced brightness due barrier opacity - Limited viewing angle
Volumetric Displays	- Autostereoscopic - Voxel based visualization - Provide full spectrum of depth cues	- Limited interactivity - Not commercially available - Low refresh rate - Eye safety issues
Electro-Holography	- Autostereoscopic - Fully parallax - Provides full spectrum of depth cues	- Requires extensive computation and bandwidth to create light field information - Not commercially available
Digital Holographic Prints	- Autostereoscopic - Fully parallax - High resolution	- Only presents static 3D images - Requires a print medium

Progress of 3D Technologies within Anatomy Education

Monoscopic visualization

Both educators and researchers use 3D display technology to visualize anatomy. Standard computer libraries such as OpenGL enable monoscopic 3D display of end user models, an example being custom hepatobiliary models (H. M. Hoffman, Murray, Irwin, & McCracken, 1996). To expedite model creation, researchers use tools including the QuickTime Virtual Reality (QTVR) framework, resulting in models such as the Yorick-VR skull (Gary L. Nieder, Scott, & Anderson, 2000), an interactive heart (Friedl et al., 2002), and libraries of organ and organ systems (Gary L Nieder, Nagy, Pearson, & Wagner, 2002) (Figure 20). Other models use CT and MRI data sets as a starting point, such as the Visible Human Program (Spitzer, Ackerman, Scherzinger, & Whitlock, 1996). Voxel-Man, a monoscopic 3D anatomical atlas, created interactive perspective views of the Visible Human data set and produced QTVR movies (Schiemann et al., 2000). More recently, research groups have created Visible Human projects for other races, including the Chinese Visible Human (Zhang, Heng, & Liu, 2006) and the Korean Visible Human (Park et al., 2005). Current projects use these newer Visible Human data sets to generate visualizations, including a 3D brain atlas (Li, Ran, Zhang, Tan, & Qiu, 2014) and a virtual model of the larynx (Liu et al., 2013).



Source: http://anatomy.uams.edu/anatomyhtml/qtvr_movs.html

Figure 20: QTVR Images of the Heart and Brain

Web-based programming tools, including the Web3D platform, VRML, WebGL, X3D, and Java 3D allow for high fidelity monoscopic 3D anatomy visualizations using standard web-browsers. Brenton et al. (2007) used these tools to create a library of 3D anatomical models for undergraduate nervous system education. The wide-spread popularity of YouTube prompted the use of streaming video with monoscopic depth cues as a tool for anatomy education (Jaffar, 2012). Commercial companies created large web-based 3D atlases as the end products. One review study found over 45 websites actively providing anatomical content (Frasca, Malezieux, Mertens, Neidhardt, & Voiglio, 2000). The review revealed that the majority of the sites were improving both in quantity and quality of anatomical content, including Biodigital Human (Qualter et al., 2011), Visible Body, Zygote Body, Google Body, Anatronica, and more. Web-based anatomical content is also available for mobile devices. A recent review highlighted many mobile applications, such as Visible Body, 3D4Medical, and Pocket Anatomy, and indicated these could be a useful tools for teaching anatomy (Lewis, Burnett, Tunstall, & Abrahams, 2014).

In August 2005, the European Computer Manufacturers Association International standardized a format to view and interact with a 3D computer object on screen, commonly referred to as Universal 3D or 3D pdf (ECMA, 2007). With a device as simple as a smartphone or tablet, one may now interact with a 3D pdf with a finger or stylus and gain the advantage of parallax. Additionally, the technology improves accessibility due to the widespread acceptance of the PDF format. The 3D PDF format has been discussed as a promising means of disseminating biomedical content (Newe, 2015; Rico, Méndez, Mavar-Haramija, Perticone, & Prats-Galino, 2014; Ruthensteiner, Baeumler, & Barnes, 2010). The format has been used to display surface cadaver models (Shin et al., 2012), the face and brain (Ziegler et al., 2011), and the radiological images (Phelps, Naeger, & Marcovici, 2012).

Extending the discussion to include human interaction with anatomical visualizations, researchers employ commercial hardware interfaces to augment interaction with visualizations. The Nintendo Wii (Luigi Gallo, De Pietro, Coronato, & Marra, 2008) and a tracking glove (L. Gallo & Ciampi, 2009) enabled interaction with monoscopic medical imaging data; the interface included actions to point, select, and rotate in the *X, Y, and Z* dimensions. More recently, Zhu et al. (2014) used the Kinect to facilitate user interaction with a web-based anatomical atlas, with user actions including translation, rotation, scaling, and taking a screenshot.

Stereoscopic visualization

Stereoscopic displays lack the widespread popularity of monoscopic 3D models, but are increasing in use as the technology becomes more commercially available. Early on, Trelease (1998) reported the use of a stereoscopic 3D display for a practical examination in gross anatomy, with anatomical structures including the thorax, abdomen, pelvic region, and upper and lower extremities. Conveniently, many of the same tools and datasets used for monoscopic 3D are also applicable for stereoscopic visualization. Using the QTVR format, Balogh et al. (2004) created stereo pairs of neurosurgical images taken during live surgery, allowing for review and education. Based upon the Visible Human dataset, researchers generated a 3D pelvis model (Sergovich, Johnson, & Wilson, 2010) and a virtual temporal bone to teach anatomy associated with cranial base surgery (R. A. Kockro & Hwang, 2009). More recently, Nobouka et al. (2014) used a stereoscopic camera system to record multi-view images of the hepatic and pancreatic regions, for use in surgical education. While widespread use of stereoscopic displays in the anatomical education field has been limited to date, the 3D data is readily available through monoscopic 3D anatomical atlases or through new technology such as stereoscopic cameras. With software and hardware available to create stereo pairs easily, the capability to use stereoscopic displays is within reach of educators and researchers.

Augmented and mixed reality visualizations

Early augmented reality prototypes applied to anatomy visualization used a video see-through HMD to display the bones of the elbow (Kancherla, Rolland, Wright, & Burdea, 1995; JP Rolland, Wright, & Kancherla, 1997). Significant issues surfaced including tracking and registering the augmented content, especially during motion of the elbow joint. Later studies focused on HMD display of internal airway anatomy overlaid upon a human patient simulator (L. Davis et al., 2002; Jannick Rolland et al., 2003) and an augmented reality display of the skull (Chien, Chen, & Jeng, 2010). Chien, Chen, and Jeng highlighted the potential in a tangible user interface', allowing a user to physically touch a model with 3D overlays, combining sensory inputs for potentially better understanding.

Mobile augmented reality displays make use of the cameras included in tablets or smart phones to record the environment for visualization and superimpose 3D visuals over existing 2D material or internal structures over a 3D object, such as an anatomical model. Using this method, researchers have successfully created mobile augmented reality for the inner ear (Zariwny, Stewart, & Dryer, 2014), cardiac anatomy (Sulaiman, 2014), and other anatomical components (Juanes et al., 2014).

A unique technology called 'mirracle' uses a technique dubbed a 'magic mirror' to enable interaction with a display through hand and arm motions, thereby moving through planes of their own body (Blum, Kleeberger, Bichlmeier, & Navab, 2012). A video system combined with a depth sensor collects data on the person standing in front of the 'magic mirror'. A screen then displays the user and augments underlying anatomical structures, allowing the user to "look inside their own body". By defining bone landmarks, researched demonstrated improved registration between the augmented visuals and the viewer's body (Meng et al., 2013).

Augmented reality presents a new twist on visualization, combining real-world visuals with computer generated overlays using a variety of techniques. The capability to display underlying anatomy and dynamic motion visualizations represents a significant tool for anatomy training and medical education (Kamphuis, Barsom, Schijven, & Christoph, 2014; Zhu, Hadadgar, Masiello, & Zary, 2014).

Autostereoscopic visualization

Autostereoscopic visualization benefits from being glasses-free, and represents significant potential in health sciences education. Early discussion by Satava and Jones (1998) proposed holography as a potential technological to augment medical education. Gorman, Meier, Rawn, and Krummel (2000) suggested that a patient based hologram could change medicine and medical education entirely, allowing physicians to visualize anatomy and practice procedures on the hologram, aptly describing the shift as "from blood and guts to bits and bytes". Recently, Khan (2014) concluded that autostereoscopic displays would be an ideal platform for medical education.

Research using such displays is emerging as the displays become more available. Using a multi-view auto-stereoscopic display, Portoni et al. (2000) created software to allow for real-time interaction with 3D medical models from the Visible Human Data set. The display used a lenticular lens over an LCD display with up to 8 views, but reported significant issues regarding resolution. Ilgner et al. (2006) used stereoscopic video taken during surgical procedures and presented it on a Sharp Mebius autostereoscopic laptop display. Recently, Christopher, William, and Cohen-Gadol

(2013) reported the first use of an autostereoscopic display for neurosurgical review. The group used a 9 view lenticular lens display. In the study, they report that the use of an autostereoscopic display is feasible due to being glasses-free and viewable by 20-30 viewers simultaneously. The authors note that the resolution is an issue due to the lenticular lens, similar to the findings of Portoni et al.

Until recently, holograms have not been sufficiently technologically mature to be usable in educational setting. In 2009, Chu et al. (2009) used a 360º motion holographic display with a rotating diffusing screen to visualize patient imagery data. Teng, Pang, Liu, and Wang (2014) created a shiftable cylindrical lens to generate holographic images, showing an exemplar model of the pelvis.

Technology Assessments: Student Perceptions, Cognitive Load, and Knowledge Gains

Simple use studies demonstrate the capability and explore the technical feasibility of 3D display in anatomy, but do not extend to the effect of the display on anatomical education. Assessment studies conducted using 3D visualization technologies generally attempt to gather data in support of two primary hypotheses: students will enjoy using and feel more confident in their skills due to the technology; and students will perform better in terms of knowledge gains, cognitive load, and spatial awareness metrics.

Student perceptions

Beginning with studies focusing on user satisfaction, Petersson, Sinkvist, Wang, and Smedby (2009) implemented a web-based monoscopic 3D anatomical application and found that students had a very positive outlook upon the visualization. Results also indicated a trend of beneficial performance results from the program. Battulga, Konishi, Tamura, and Moriguchi (2012) also studied online monoscopic 3D computer models; the findings indicated the interactive models had positive effects on medical education and suggested that monoscopic 3D computer models are more efficient than textbooks alone in medical education. The authors also suggest the 3D technology can motivate students to understand complex anatomical structures. Tourancheau et al. (2012) focused on the quality of experience when using a stereoscopic 3D display and an autostereoscopic multi-view display for anatomy display. The results indicated the population felt 3D displays were beneficial for their work, but that visual fatigue and discomfort were issues affecting user experience. Brown, Hamilton, and Denison (2012) created a stereoscopic visualization of an aorta and a ruptured aorta, reporting that students felt the system aided their understanding of anatomy and pathology and provided an advantage compared to current anatomy classes.

Focusing on topics related to students' perceived confidence, Thomas, Denham, and Dinolfo (2011) found that students using web-based monoscopic 3D visualizations as part of a gross anatomy lab perceived an improved ability to name major anatomical structures from memory, to draw major anatomical structures from memory, and to explain major anatomical relationships from memory. Yao et al. (2014) compared groups using 2D CT scans of sinus anatomy and a reconstructed 3D visualization of the scans. The group using the 3D reconstruction had higher perceived understanding of the content and believed the technology accelerated their understanding of sinus anatomy. A study from Ruisoto, Mendez, and Galino (2014) involved students using a tool to explore 3D models of neuroanatomy; participants reported perceiving the tool as having a high level of educational value.

A subset of publications studied student perceptions within the framework of technology acceptance. Technology acceptance seeks to predict the future adoption level of a technology based on perceived usefulness, perceived ease of use, and intention to use (Fred D. Davis, 1989; F. D. Davis, Bagozzi, & Warshaw, 1989; Venkatesh & Davis, 2000). A study by Huang, Liaw, and Lai (2013) used these metrics to assess a 3D stereoscopic projection of anatomical content to an entire classroom, and then monoscopic 3D models in individual self-guided sessions. The results indicated that an imagination metric, closely related to spatial visualization, was the largest contributor to perceived usefulness. The students rated the technology highly, with positive perceptions related to perceived ease of use, perceived usefulness, and intent to use. Rasimah, Ahmad, and Zaman (2011) conducted a technology acceptance evaluation of an augmented reality system for biomedical science students learning tissue engineering concepts. The system employed a webcam paired with a monoscopic 3D visualization, and overlaid computer generated graphics on the video feed from the webcam. The participants reported a high level of technology acceptance, including positive rating for perceived usefulness, perceived ease of use, and intent to use. Yeom et al (2013) evaluated the combination of monoscopic 3D models and a haptic device to determine whether medical students accepted the haptic interface for 3D exploration. The results indicted perceived ease of use and perceived usefulness were both positive for the display and haptic interface.

Student performance

In addition to student perceptions, many studies focus on performance measures, such as knowledge gains. Beginning with monoscopic 3D visualization, Nicholson, Chalk, Funnel, and Daniel (2009) reported the use and study of a monoscopic 3D model of the ear produced significant learning gains among students on post-test material. Similar studies comparing monoscopic 3D to standard 2D material have found significant performance improvements for other anatomical structures including the brain (Estevez, Lindgren, & Bergethon, 2010) and the liver (Muller-Stich et al., 2013). In a study comparing monoscopic 3D models against traditional cadaver instruction, Codd and Choudhury (2011) found no significant difference in the two groups, indicating that virtual reality anatomy can be used to compliment traditional methods effectively. Using monoscopic 3D models on mobile displays, Noguera, Jimenez, and Osuna-Perez (2013) generated content to train manual therapy. The researchers conducted an outcomes study, which found students studying the knee in 3D performed better on post-tests compared to those using the 2D representations. Additionally, participants reported high levels of user satisfaction. Augmented reality has been sparsely evaluated; a single assessment study found that students using an augmented textbook demonstrated improved lower limb knowledge and improved motivation (Ferrer-Torregrosa, Torralba, Jimenez, García, & Barcia, 2014).

Another measure of performance is anatomical structure localization and identification. Beerman et al. (2010), presented students with 2D CT images or 3D representations of the liver. The results showed the 3D representation resulted in significant improvements during identification of complex liver anatomy, with men showing a larger increase than women. Settapat, Achalakul, and Ohkura (2014) created a web-based monoscopic 3D medical image visualization framework with a focus on biomedical engineering students. Within the study, students visualized medical imaging in 2D and through the monoscopic 3D visualization tool. The results reported students using the 3D tool had a higher percentage of correct answers when asked to locate brain structures. Additionally, students felt the material was easier to learn in 3D and indicated that 3D visualization was preferred for education to the standard 2D image tools. Focusing on pathology, Jurgaitas et al. (2008), studied the tumor localization in the liver. The results indicate that students achieved better improved tumor localization when using the 3D monoscopic visualization compared to 2D CT images, and planned a more precise tumor surgery.

A metric related to improved anatomical knowledge is response time. Ruisoto et al. (2012) focused on localization of brain structures within monoscopic 3D visualizations compared against 2D cross-sectional visualizations. The study found that the percentage of correct answers and response time were significantly better in the group that used the 3D visualization. A study of liver anatomy conducted by Muller-Stich et al. (2013) found significant improvement of monoscopic 3D over 2D visualization in post-test results. The study also found participants in the 3D group answered questions significantly faster. Faster response times in these studies could indicate increased student confidence or improved access to learned content due to 3D visualization.

Shifting to from monoscopic 3D representations to stereoscopic displays, Luursema et al. (2006) compared a stereoscopic 3D display with a 2D display and reported significant improvement of anatomical structure identification due to the stereoscopic 3D display. Additionally, this study found that users of low visual-spatial ability had significantly improved results, indicating that the use of 3D may help students with low VSA to overcome visualization difficulties. In a follow up experiment, the group found that displays using computer generated stereopsis provided a significant benefit to an anatomical localization task of the pelvic region; however, visual-spatial ability was still the primary performance driver (Luursema, Verwey, Kommers, & Annema, 2008). Hilbelink (2009) conducted a study comparing color anaglyph stereoscopic 3D to a 2D representation of the skull. Results showed significant improvement in identification of structures and knowledge of spatial relationships.

Focusing on the final display category of autostereoscopic displays, Abildgaard et al. (2010), found that an autostereoscopic, parallax barrier display benefited the visualization and identification of arteries when studying angiography. Leung, Lee, Mark, and Lui (2012) also used a parallax barrier display, but focused on students learning epidemiology and the 3D shape of viruses. The results showed using an autostereoscopic display allowed students to better remember and recreate the shape of viruses.

Cognitive load

In addition to knowledge gains, one notable metric in education is cognitive load, defined as the mental effort expended to conduct a task (J Sweller, 1994). The ideal findings for a visualization tool are a reduction in cognitive load and an increase in performance; in other words, the work is easier and the results are better. Researchers want to understand how 3D visualization affects cognitive load in anatomy training and spatial learning.

A series of studies conducted in the late 1990s and early 2000s sought to determine the relationship between cognitive load, 3D visualization, and visual-spatial ability (A. Garg et al., 1999; G. N. Garg, Lawrence Spero, Ian Taylor, Amit, 1999). The initial studies found that multi-view monoscopic 3D representations showed no improvement over key view monoscopic 3D representations, indicating that the benefit of computer based models may be limited in terms of spatial learning. However, subsequent studies found students showed improved spatial knowledge using a multi-view monoscopic 3D visualization of carpal anatomy with rotation-based interactivity (A. X. Garg et al., 2001).

Recent studies have returned to the topic of cognitive load. Foo et al. (2013) used monoscopic 3D models of the gallbladder, celiac trunk, and superior mesenteric artery, focusing on localization tasks of the anatomical structures. The study found participants in the 3D group had improved localization and reduced mental demand using the NASA-Task Load Index(TLX) cognitive load scale. In a study using print holograms of cardiac anatomy, Hackett (2013) reported an improvement in post-test performance and a reduction in cognitive load. The study also reported on cognitive efficiency, a metric combining performance and cognitive load; it was determined that the holograms provided significant improvement in cognitive efficiency over traditional 2D textbook materials. In a follow-up study from Hackett and Fefferman (2014), researchers displayed cardiac anatomy and neuroanatomy, comparing a dynamic holographic display with commercial 3D stereoscopic televisions using active-shuttering glasses. Results showed participants were able to assess anatomical dimensions more quickly and more accurately using the holographic display, possibly indicating more rapid cognitive processing due to the autostereoscopic display.

Mixed and neutral results

While many studies show the benefits of 3D visualization, the findings are not uniform. The initial studies by Garg et al. (1999a, 1999b) indicated a mixed result, showing no significant difference due to the monoscopic 3D models. Metzler et al. (2012) conducted an experiment to determine if studying 3D images would improve interpretation of 2D medical imaging, finding no difference between the 2D and 3D groups. While the result is significant, since the study focused on interpretation of 2D imaging, the spatial relationships learned in the 3D training may have been unused. Studies focusing on the larynx (Hu et al., 2010; Tan et al., 2012), the liver (Keedy et al., 2011), and cranial nerves (Yeung, Fung, & Wilson, 2012) found no significant difference in performance between a monoscopic 3D anatomical presentation and traditional textbook materials; however, all studies indicated students preferred using the 3D models. Yeung et al. also suggested these models may be beneficial by helping pique student interest. Hoyek et al. (2014) performed a study on monoscopic 3D animations focused on trunk and limb assessment. The study had mixed results, with students using a 2D drawing representation performing better on the trunk assessment. However, students performed better in terms of spatial understanding using the 3D animations.

Regarding stereoscopic displays, a study from Al-Khalil and Coppoc (2014) found no significant difference in post-test results when studying using a 2D video compared to a 3D stereoscopic video. The study focused on veterinary anatomy, but the results may translate to human anatomy. Kockro et al. (2015) used a polarization interlaced stereoscopic display for teaching neuroanatomy. The study found medical students preferred the 3D visualization to 2D PowerPoint material, but there was not a statistically significant difference in learning gains.

Conclusion

This literature review began with a primer on the human visual system and the depth cues used to perceive depth. The review thoroughly explains the visualization technologies employed in contemporary 3D displays, including the depth cues they exhibit. The displays include monoscopic depth cues on 2D screens (2.5D), stereoscopic displays, augmented reality, autostereoscopic displays, and holographic displays. The pros and cons of these displays are highlighted by Table 3 and illustrate that there is no current ‘perfect display’.

Tables 4, 5, 6, and 7 summarize the assessment studies, including the anatomical structure(s) used in the study, the 3D visualization technology, and the major findings. From the literature review, 32 articles reported cases of simple 3D display use, with another seven articles discussing the potential for 3D display technologies within anatomical education. Beyond simple use and theoretic discussions, another 38 articles reported assessment of 3D display technologies based on student perceptions, cognitive load, and performance improvements. The majority of assessment research, 28 publications representing 74% of the assessment studies, concluded 3D display technology had beneficial results when used in anatomical education settings. These findings align with the meta-analysis conducted by Yammine and Violato (2014). Six articles reported mixed results (16%) and four articles reported no positive effects due to 3D (10%). No studies indicated 3D visualization caused an adverse effect on student perception, cognitive load, or performance.

Table 4: Beneficial Perception Results of 3D Visualization

Reference	Anatomy	3D Visualization	Major Findings
Petersson et al., 2009	Vasculature	Monoscopic	- Trend of improved learning gains - Positive student perception of technology
Battulga et al., 2012	General	Monoscopic	- Positive student perceptions - Potential improvement in student motivation
Tourancheau et al., 2012	General	Stereoscopic and Multi-View Autostereoscopic	- Positive perceptions from medical doctors
Brown et al., 2012	Aorta	Polarization Interlaced Stereoscopic	- Positive student perception of system and education value
Thomas et al., 2011	Various	Monoscopic	- Improved student perception of their ability to name, draw, and explain major anatomical structures
Yao et al., 2014	Sinus	Monoscopic	- Higher perceived understanding of anatomy - Students believed the technology accelerated their understanding of sinus anatomy
Ruisoto et al., 2014	Neuro-anatomy	Monoscopic	- Students rated visualization tool as high level of educational value
Huang et al., 2013	Multiple Systems	Stereoscopic and Monoscopic	- High degree of perceived usefulness and perceived ease of use
Rasimah et al., 2011	Tissue Properties	Augmented Reality	- High willingness to use 3D technology - Perceived ease of use and perceived usefulness both showed positive results
Yeom et al., 2013	General	Monoscopic	- Paired a haptic interface with 3D visualization - High levels of perceived usefulness and perceived ease of use

Table 5: Beneficial Performance Results of 3D Visualization

Reference	Anatomy	3D Visualization	Major Findings
Nicholson et al., 2006	Inner Ear	Monoscopic	- Improved post-test performance - Positive student perception of technology
Estevez et al., 2010	Neuro-anatomy	Monoscopic	- Improved 3D spatial understanding - Students preferred 3D presentation
Muller-Stich et al., 2013	Liver	Monoscopic	- Improved post-test performance - Faster student response time
Codd & Choudhury, 2011	Forearm	Monoscopic	- Comparable to use of dissection and textbooks - Positive feedback from users
Noguera et al., 2013	Manual Therapy of the Knee	Monoscopic	- Improved post-test performance - High levels of user satisfaction
Beerman et al., 2010	Liver	Monoscopic	- Improved performance on identification tasks
Settapat et al., 2014	Brain	Monoscopic	- Improved performance on identification tasks - Students felt 3D content was easier to learn - Students preferred 3D visualization to 2D
Jurgaitis et al., 2008	Liver	Monoscopic	- Improved tumor localization
Ruisoto et al., 2012	Neuro-anatomy	Monoscopic	- Improved performance on post-test - Faster student response time
Foo et al., 2013	Gallbladder; Celiac Trunk	Monoscopic	- Improvement on anatomical localization tasks - Reduced mental effort using NASA-TLX scale
Luursema et al., 2006; Luursema et al., 2008	Abdomen	Time-Multiplexed Stereoscopic	- Improved performance on identification tasks - Beneficial for participants with low visual-spatial ability
Hilbelink, 2008	Skull	Color Anaglyph Stereoscopic	- Improved student performance in anatomical identification and spatial relationships
Abildgaard et al., 2010	Vasculature	Autostereoscopic Parallax Barrier	- Improved performance on identification of arteries
Leung et al., 2012	Viral Structures	Autostereoscopic Parallax Barrier	- Improved retention and ability to recreate viral shapes
Ferrer-Torregros et al., 2014	Lower Limb	Augmented Reality Textbook	- Positive student motivation - Improved performance on post test
Hackett, 2013	Cardiac Anatomy	Digital Holograms	- Improved post-test performance - Trend of reduced cognitive load - Improved cognitive efficiency
Hackett & Fefferman, 2014	Cardiac and Neuro-anatomy	Dynamic Holographic Display	- Reduced time to assess anatomical dimensions - Improved accuracy when students determined anatomical dimensions

Table 6: Mixed Results of 3D Visualization

Reference	Anatomy	Visualization Technique	Major Findings
Garg et al., 1999; Garg et al., 2001	Carpal bones	Monoscopic	- No difference between multi-view 3D models and key view models - Later study found students had better spatial awareness with multi-view 3D using rotation interaction
Hu et al., 2010	Larynx	Monoscopic	- Improved student perception - No difference in performance
Keedy et al., 2011	Liver	Monoscopic	- Students reported higher satisfaction for 3D visualization - No difference in performance over traditional textbook materials
Hoyek et al., 2014	Limb and Trunk Assessment	Monoscopic	- Traditional 2D representation led to improved performance on trunk assessment - 3D visualization results in improved spatial understanding of anatomy
Kockro et al., 2015	Neuro-anatomy	Stereoscopic	- Students preferred using 3D visualization - No statistically significant learning gains due to 3D use

Table 7: No Effect Results of 3D Visualization

Reference	Anatomy	Visualization Technique	Major Findings
Metzler et al., 2012	Liver	Monoscopic	- Correct interpretation of 2D imaging does not differ in students trained in 3D or 2D
Tan et al., 2012	Larynx	Monoscopic	- 3D representations and 2D images were equivalent in performance and spatial understanding
Yeung et al., 2012	Cranial Nerve	Monoscopic	- No significant different between traditional text/image-based instruction and the 3D tool.
Al-Khalil & Coppoc, 2014	Veterinary	Stereoscopic Video	- No significant difference on post-test results between 3D video and 2D Video

While the majority of anatomy research indicates 3D provides beneficial results, further research would solidify this position. Research articles on stereoscopic, autostereoscopic, and augmented reality displays in education are presently underrepresented. Possible rationale for the limited research may be technical immaturity, lack of availability, and higher cost associated with these display variants. Additionally, for many years, the quality of these displays in terms of resolution and refresh rate was poor, making them unappealing and ill-suited to high resolution anatomical models. The potential capabilities of newer displays include a more complete sense of 3D perception and eliminating common issues associated with 3D displays, such as convergence accommodation conflict. Studies are needed to determine whether the added cost and complexity of autostereoscopic and augmented reality displays, when compared with their additional 3D capability, represent a value added proposition.

Studies employing frameworks of technology acceptance and technology adoption seek to predict the potential for successful adoption and identify deficiencies in a particular technology (Straub, 2009). Huang et al. (2013), Rasimah et al. (2011), and Yeom et al. (2013) used the technology acceptance model to assess adoption of 3D displays in anatomy education, with all studies indicating a high degree of potential adoption. None of the articles utilized alternative frameworks for technology adoption, such as the concerns-based adoption model (Hall, Loucks, Rutherford, & Newlove, 1975) or innovation diffusion theory (Rogers & Shoemaker, 1971).

Comparison studies between 3D modalities, such as comparing monoscopic 3D to stereoscopic 3D, may determine which 3D modality is ideal for anatomical education. The answer may depend on other factors, such as user group characteristics and the operating environment. Such studies would help derive future requirements regarding resolution, refresh rate, and other pertinent display metrics, guiding future technical development.

Notably, the majority of assessment research focused on short term exposure to a 3D display and immediate assessment of knowledge gains and student perception. Longitudinal studies focusing on long term retention, knowledge decay, and transfer of knowledge to clinical skills are absent. The question of whether 3D visualization impacts long term knowledge acquisition is unanswered.

Interaction as a dependent variable was rarely included in studies. Research related to the impact of virtual rotation, dissection, virtual exploration, and other interaction, is largely unexplored, especially in newer display technologies. Studies may include interaction, such as using a simulator to teach anatomy (Hariri, Rawn, Srivastava, Youngblood, & Ladd, 2004), but don't compare to a baseline of non-interaction or other interaction modes.

Related to interaction, literature gaps exist related to the effect of 3D interfaces, in both hardware and software capabilities. The status quo of mouse and keyboard may not represent the optimal interface for 3D visualizations. Exploration of interface platforms, including the Wii (Luigi Gallo et al., 2008), a data glove (L. Gallo & Ciampi, 2009), and the Kinect (H. Zhu et al., 2014), with 3D anatomy lacked evaluation of usability or performance improvement. Further, the continuing evolution of technology is supplying many new interface platforms, including the Kinect 2, Myo arm bands, Leap motion, and others, which may represent more intuitive interfaces for interacting with 3D anatomical visualizations, and therefore warrant further study.

In conclusion, the majority of research indicates 3D display have significant potential for positively impacting anatomical education. Monoscopic, stereoscopic, autostereoscopic, and augmented reality displays have demonstrated benefits, though newer display modalities have far fewer associated studies. Literature gaps exist related to new display technologies, alternative technology adoption frameworks, interaction paradigms, longitudinal studies, and comparisons between display variants.

CHAPTER 3: METHODOLOGY

Based on the noted gaps in anatomy visualization, this dissertation focuses on the use of autostereoscopic holographic visualization in learning anatomy. The experiment compares color holographic prints, monoscopic spatial perception with kinetic depth effect via touchscreen display of a color model, and monoscopic spatial perception found in traditional color anatomical textbook materials. Metrics of particular interest include usability, technology acceptance, cognitive load, knowledge performance, confidence, and visual spatial ability. In addition, the study analyzes the correlation between VSA and test performance. The individual metrics of interest are discussed in detail in the following sections, including the associated research questions, hypotheses, and instruments.

Demographics

Demographics of the population will be collected, including age, gender, and handedness. The demographic survey is shown an appendix F.

Usability

System usability is defined in ISO 9241 draft standard as the ‘‘extent to which a product can be used with effectiveness, efficiency and satisfaction in a specified context of used’’ (Abran, Khelifi, Suryn, & Seffah, 2003). Usability studies are formative or summative in nature. Formative studies take place during development and allow for iterative improvements by identifying usability issues. Summative studies use a finalize product to test whether the usability goals of the project are met (Albert & Tullis, 2013). In particular, usability metrics focusing on ease of use, ease of learning, and user satisfaction are of particular interest. After using the holograms, users completed a post-test survey using a Likert scale. A typical item in a Likert scale is a statement that responders rate their level of agreement, commonly on a scale of one to five, seven, or nine (Likert, 1932). The survey questions used in this experiment are from the system usability scale, a widely used instrument with a reliability of 0.85 (Bangor, Kortum, & Miller, 2008), shown in appendix B.

1. *Research Question: Does the use of holograms for anatomical education result in high levels of user satisfaction?*

   Hypothesis 1: Users will feel the holograms are easy to use.

2. *Research Question: Does the use of holograms for anatomical education result in higher levels of user satisfaction compared to monoscopic spatial perception via printed images?*

   Hypothesis 2: Users will feel the holograms are easier to use than printed images.

3. *Research Question: Does the use of holograms for anatomical education result in higher levels of user satisfaction compared to monoscopic spatial perception with kinetic depth effect via computer models?*

   Hypothesis 3: Users will feel the holograms are easier to use than monoscopic computer models with kinetic depth effect.

Technology Acceptance

While the goal of many research projects is to expand the knowledge base, another goal is to transition a technology into the community for use. A key component to technology adoption is the acceptance and positive perception within the user group. The Technology Acceptance Model

(TAM) seeks to predict technology adoption using two metrics: perceived ease of use and perceived usefulness (Fred D Davis, 1989). The framework was extended to use other measures, including intent to use (Venkatesh & Davis, 2000). Using these metrics, researchers derive the general acceptance of the technology and the potential for adoption if the technology were provided. The instrument is composed of a series of Likert scale items focused on perceived ease of use, perceived usefulness, and intent to use, based on the questionnaire developed by Venkatesh and Davis. Cronbach's alpha for these are as follows: perceived ease of use (α=0.86 to 0.98); perceived usefulness (α=0.87 to 0.98); intent to use (α=0.82 to 0.97). The instrument for this is included in appendix B along with the usability instrument.

4. *Research Question: Do students exhibit a high level of technology acceptance for holograms in the realm of anatomy training?*

   Hypothesis 4: Students exhibit a high level of technology acceptance for holograms in the realm of anatomy training.

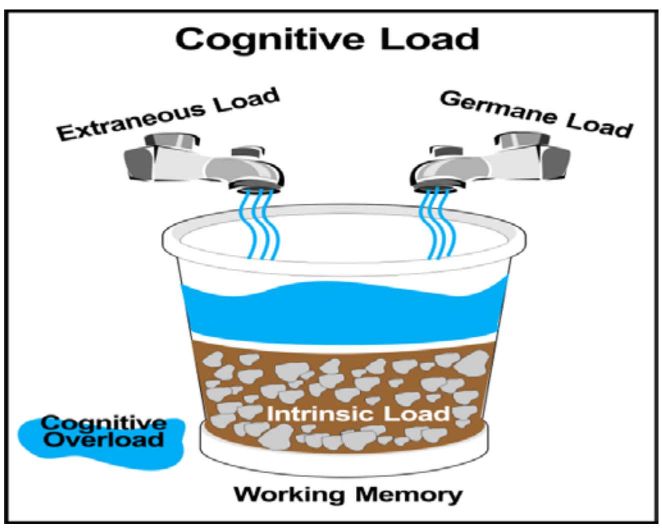
Cognitive Load

Cognitive load is the load imposed upon the working memory by executive processes (J Sweller, 1994). Cognitive Load Theory (CLT) relies on the model of human information processing, which occurs through three types of memory: sensory memory, working memory, and long-term memory. Sensory memory originates from sensory organs, such as the eyes and ears, and lasts only a few seconds. Working memory provides processing of the information from sensory memory. Working memory has significant limitations in terms of size and duration (Simon, 1974) holding only seven items or elements at a time (Miller, 1956). The brain moves the information from working memory into long-term memory through the use of organizational schemas, which categorize the information in the manner it will be used (Chi, Feltovich, & Glaser, 1981). Other research discusses this information organization conceptually as chunks (Miller, 1956) or scripts (Schank & Abelson, 2013); however, they are functionally the same concept.

In order to optimize the presentation of information, CLT targets the working memory process where cognitive load exists. The central tenet of CLT is that working memory can be overloaded with information, resulting in decreased learning performance. Conversely, by reducing cognitive load, additional learning processes can occur. Within CLT, cognitive load is split into three sub-components: intrinsic cognitive load, germane cognitive load, and extraneous cognitive load (J. Sweller, 1988). Intrinsic cognitive load relates to the inherent characteristics of the content (J Sweller, 1994), such as the number of elements or element interactivity. Studies show that instruction design changes cannot alter intrinsic cognitive load (Ayres, 2006; F. Paas, Tuovinen, Tabbers, & Van Gerven, 2003). For example, intrinsic load during anatomy training results from a high amount of information, but a relatively low interaction between the learning elements (J. Sweller, van Merrienboer, & Paas, 1998). As a result, learning the names of individual muscles, bones, nerves, etc., does not impose a high cognitive load, but manipulating these into usable units for understanding spatial and functional relationships results in extensive intrinsic cognitive load (Khalil, Paas, Johnson, & Payer, 2005).

Germane load focuses on converting the information within working memory into schemas for storage in long term memory. Germane load is incredibly important because it directly relates to learning processes, including the construction of schemas and the automation of schemas (J. Van Merriënboer, Schuurman, De Croock, & Paas, 2002). The tasks involved in the construction of schemas include interpreting, exemplifying, classifying, inferring, differentiating, and organizing information (Mayer, 2002). The goal of instructional designers is to encourage these learning processes to the utmost extent.

The final component of cognitive load is extraneous cognitive load. Extraneous load is load not related to learning and can be altered by instructional interventions (van Merrienboer & Sweller, 2005). The vast majority of research focuses on reducing extraneous cognitive load within information presentations. The goal of reducing extraneous cognitive load is ultimately to reduce time and mental resources wasted during processing of excess information. The combination of extraneous load, germane load, and intrinsic load comprise overall cognitive load; when the cognitive load imposed exceeds the capacity of the working memory, cognitive overload occurs (Figure 21). The presentation of medical holograms may impact both germane and extraneous processes.



Source: (Hackett, 2013)

Figure 21: Cognitive Load Illustrated

A related theory to CLT is the cognitive theory of multimedia learning (CTML) (Mayer, 2005). CTML is based on three cognitive principles of learning: dual channel processing for visual and auditory processing, each channel has limited processing capacity, and active learning requires a coordinated set of cognitive processes during learning. CTML and CLT are consistent with one another, with CLT suggesting similar notions, especially in regards to the limits of working memory being a primary driver of learning. One of the primary difference between CLT and CTML is the focus of CTML on the kinds of information processes, rather than cognitive load as a whole.

One of the most common methods for determining cognitive load is a self-reported metric of mental effort. After post-treatment testing, participants reported their perceived cognitive load and overall workload using the NASA TLX (Hart & Staveland, 1988). The instrument has shown reliability of 0.74. The instrument is shown in appendix C.

5. *Research Question: Does the use of holograms for anatomical education result in changes in the cognitive load of participants?*

   Hypothesis 5: Using the holograms will result in lower levels of cognitive load compared to printed images and monoscopic computer models with kinetic depth effect.

Anatomical Knowledge Gains

The desire to improve anatomical education lies at the heart of this research effort. The immediate measure of anatomical knowledge is test performance. Using a pre-test / post-test methodology, researchers may determine a student's knowledge gains. In this case, the pre-test and post-test will include the same questions, but in a different order. The students will also have a delay from their period of study, to remove the effect of immediate recall. The areas of interest will be cardiac anatomy, including the valves and major vessels of the heart. The instrument for pre- and post-test is shown in appendix G and H. The test was developed with instructors of the nursing program.

6. *Research Question: Do students using holograms demonstrate improved gains in spatial anatomical knowledge compared to monoscopic spatial perception via printed images?*

   Hypothesis 6: Students using holograms demonstrate improved gains in spatial anatomical knowledge based on post-test results, when compared with post-test results using printed images.

7. *Research Question: Do students using holograms demonstrate improved gains in spatial anatomical knowledge compared to monoscopic spatial perception with kinetic depth effect via computer models?*

   Hypothesis 7: Students using holograms demonstrate improved gains in spatial anatomical knowledge based on post-test results, when compared with post-test results using monoscopic computer models with kinetic depth effect.

Confidence

Student confidence in learned material is a vital component to education, especially medical education. Remembering the aforementioned studies which found that the majority of students felt insecure in their knowledge of anatomy, improving student confidence is an important concept. Within this study, a single Likert-scale item was used to assess confidence in cardiac anatomy before the study period and following the study period. The single item was included at the end of the demographics survey and the end of the technology acceptance instrument.

8. *Research Question: Do students using holograms demonstrate improved confidence related to anatomical knowledge when compared with printed images and 3DPDF?*
   Hypothesis 8: Students using holograms will demonstrate improved ability to identify anatomical structures and nomenclature, compared to monoscopic 3D models with kinetic depth effect.

Visual Spatial Ability

Spatial and visual perception abilities are "concerned with an individual's abilities to search the visual field, apprehend the forms, shapes, and positions of objects as visually perceived, forming mental representations of those forms, shapes, and positions, and manipulating those mental representations" (Carroll, 1993). Thus, spatial ability is not a single attribute, but a collection of specific skills related to visualization and spatial cognition (Voyer, Voyer, & Bryden, 1995). These visual skills include: spatial ability, mental rotation, spatial perception, and spatial visualization (Linn & Petersen, 1985). Spatial ability is defined as over-arching concept that generally refers to skill in representing, transforming, generating, and recalling symbolic, nonlinguistic information. Mental rotation involves the ability to rapidly and accurately rotate a 2D or 3D figure. Spatial perception is person's ability to determine spatial relationships with respect to the orientation of his or her own body. Lastly, spatial visualization involves complicated, multi-step manipulations of spatially presented information. These tasks require analysis of the relationship between different spatial representations, rather than a matching of those representations. Mental rotation and spatial perception may or may not be elements of the analytic strategy required to complete the task (Bogue & Marra, 2003).

Visual spatial ability and the associated skills are important to learning anatomy (A. X. Garg et al., 2001; Guillot, Champely, Batier, Thiriet, & Collet, 2007; N. Hoyek et al., 2009; Langlois et al., 2009), and may be predictors for success related to surgical and other clinical skills (Hegarty, Keehner, Cohen, Montello, & Lippa, 2007; Kyle R. Wanzel, Hamstra, Anastakis, Matsumoto, & Cusimano, 2002; Kyle R Wanzel et al., 2003). To determine an individual's VSA, there are a wide variety of tests that may be conducted. To determine spatial visualization ability, the instrument VZ-2 Paper Folding test from ETS will be used. This instrument has been validated and shown to consistently load onto factors related to spatial visualization (Carroll, 1993). The instrument is shown in appendix D. Additionally, the card rotation test will be used, which has also been validated and shown to consistently load onto factors related to spatial visualization (Carroll, 1993). The instrument is shown in appendix E. This dissertation seeks to answer the following research questions related to VSA and the relationship with autostereoscopic holograms.

9. *Research Question: Is there a relationship between an individual's VSA and their performance when using holograms?*

   Hypothesis 9: There is a relationship between an individual's VSA and their performance using holograms.

10. *Research Question: Do students with a low VSA have increased benefit from the addition of 3D holographic content compared to students with high VSA?*

    Hypothesis 10: Students with low VSA show larger improvements due to the addition of 3D holographic content compared to students with high VSA.

Description of Technologies

The model used is a model of the heart generated using Maya. The model is in the .OBJ format. The same model was used as the basis for the printed images, 3D PDF file, and holographic prints. The printed images will include 4 views of the heart: one of the full heart, one of the full heart with labels, one of the heart cutaway to reveal the valves, and one of the heart cutaway with labels.

The monoscopic 3D models used will be in the 3D PDF format. The 3D PDF was generated from the same model as the printed images. The 3D PDF was generated using the PDF3D ReportGen software, which imported the .OBJ file and converted it into an interactive 3D PDF. The 3D PDF will be presented on a laptop screen, an HP Elitebook 8770W with a 17.3" display. The 3D PDF software used for viewing and interaction is Adobe Reader.

The holographic technology used will be autostereoscopic holographic prints. The holographic prints are full-color, fully parallax, and static. The holograms will have two views included, one printed on the front of side of the holographic print and one on the reverse side. The front view is the full heart with labels, and the back view is the cutaway heart with labels. The holograms used in this experiment measure 12" X 12". The lighting source is a white LED bulb positioned eighteen inches from the hologram, which is built into a light stand. To switch between views, the participant picks up the holographic print, flips the hologram, and inserts it back into the light stand. The setup is shown in Figure 22, with the front view, the hologram being flipped, and the back view.

Figure 22: Hologram in Light Stand

Experimental Design

The experimental study will be conducted at the Medical Education and Training Campus (METC), in San Antonio, TX. Participants will be first year nursing students, with limited anatomical knowledge. The steps within the experiment and the associated time requirements are detailed in Table 8.

Table 8: Experimental Design

Task	Time Required
1. Participants complete informed consent forms	5 minutes
2. Participants complete pre-test and demographics.	10 minutes
3. Participants given study material. Group 1 receives printed images, group 2 receives monoscopic 3D, and group 3 receives holograms.	5 minutes
4. Participants complete cognitive load instrument.	4 minutes
5. Participants complete VSA instruments.	6 minutes
6. Participants complete technology acceptance and usability instruments.	5 minutes
7. Participants complete post test.	10 minutes
Total Time	45 minutes

The study design assumes a medium effect size, α=.05, and β=.2. Participants will be split into three groups via simple randomization procedures (computerized random numbers). To determine the total number of participants necessary, Cohen outlined the number of participants needed for statistical significance in various tests and at various effect sizes (Cohen, 1992). Using Cohen's finding and the aforementioned statistical parameters, a test for the difference between multiple means will be used on the anatomical test scores, usability, technology acceptance, and cognitive load scores and will require at least 52 participants in each group, totaling 156 participants. To determine the correlation between VSA and the anatomical performance scores, Pearson's r will be used. Cohen suggests using at least 67 participants total for this statistical test.

CHAPTER 4: RESULTS

The data collection for this experiment took place at the Nursing Science Building at the METC from June 2017 through Oct 2017. A total of 182 participants volunteered for the experiment, randomized into three groups: printed images, 3DPDF, and holograms. Three participants were excluded from the final results: one left the study due to a prior medical appointment and two were disqualified for using study material during the testing period. After exclusions, the final sample sizes were n=59 for printed images, n=60 for 3D PDF, and n=60 for holograms. The study population included 96 men and 83 women, with a mean age of 22.3 (Table 9).

Table 9: Population Demographics

Average Age	22.3M ± 4.6SD Years
Gender	Male: 96 Female: 83
Dominant Hand	Left: 25 Right: 154

Analysis Technique

Analysis focused on post-test scores, mental effort values, technology acceptance measures, usability measures, and VSA test scores. All analyses were conducted using SPSS version 24. Nonparametric statistics were employed due to the lack of normality inherent to Likert scale data such as the NASA TLX and the technology acceptance instrument. Nonparametric statistics were employed on the post-test comparisons due to a group of outliers in the hologram treatment, which researchers chose not to exclude for reasons of completeness.

Post-test scores were compared using a Kruskal-Walllis test, followed by post-hoc Mann-Whitney tests. Three post-hoc comparisons were made, so a Bonferroni correction was applied, shifting the level of significance tested against from .05 to .0167. The same analysis technique was applied for mental effort, usability, confidence, and technology acceptance.

In addition to raw test scores, researchers analyzed the number of passing scores for each of the three conditions, using a between-groups Chi-Square test, followed by post-hoc pairwise Chi-Square analyses. Passing was determined as a score of 70% or greater, as specified by the nursing program. The odds ratio was computed to determine the effect size of the pairwise associations.

The relationship between VSA and the ability to learn spatial anatomy is noteworthy. VSA was measured with both the paper-folding test and the card-rotation test. The correlation between each of these scores and the post-test score was analyzed using Spearman's Rho. Additionally, researchers sought to determine the effect of these visualization treatments on students with low visual-spatial ability compared to the rest of the test population. The score on the paper-folding exam was used to separate the participants into quintiles, with the lowest quintile representing students with low visual-spatial ability. The difference between post-test scores and the score improvement was compared for the low quintile against the other four quintiles using a series of Mann-Whitney pairwise comparisons.

Lastly, researchers computed the efficiency of instructional condition, which is a composite metric combining performance and mental effort. The technique converts performance and mental effort to z-scores, allowing for relative condition efficiency to be compared (F. G. Paas & Van Merriënboer, 1993). A Kruskal-Wallis test and post-hoc Mann-Whitney tests were conducted on this computed measure.

Usability

Usability was assessed using questions from the System Usability Scale. Question response values were averaged for each participant, with more positive values indicating more positive response. These values were used to assess the follow hypotheses:

Hypothesis 1: Users will feel the holograms are easy to use.

Hypothesis 2: Users will feel the holograms are easier to use than printed images.

Hypothesis 3: Users will feel the holograms are easier to use than monoscopic computer models with kinetic depth effect.

Results indicated that the participant's usability response was affected by the display modality ($H(3) = 15.184$; $p = .001$)(Table 10). Compared to printed images (*Mdn.* = 4.0), participants felt both the holograms (*Mdn.* = 4.67; $U = 1026.5$, $p < .001$; $r = .36$) and the 3DPDFs (*Mdn.* = 4.5; $U = 1265.5$; $p = .007$; $r = .25$) had better usability. There was no significant difference between the usability of the 3DPDF and holograms treatment ($p = .443$).

Technology Acceptance

Closely related to usability, technology acceptance focuses on user perceptions of technology in terms of ease of use, usefulness, and intent to use. The individual metrics as well as a combined technology acceptance score was compared across treatment groups. This data was used to assess the following hypothesis:

Hypothesis 4: Students exhibit a high level of technology acceptance for holograms in the realm of anatomy training.

Results indicated that the participant's technology acceptance was affected by the display modality across all modalities (Table 10). There was a significant difference for overall technology acceptance ($H(3) = 16.75$, $p < .001$), perceive ease of use ($H(3) = 23.8$, $p < .001$), perceived usefulness ($H(3) = 7.75$, $p = .021$), and intent to use ($H(3) = 7.17$, $p = .028$).

Table 10: Usability and Technology Acceptance Measures

Measure	Holograms (1)	3D PDF (2)	Printed Images (3)	Between Treatment Statistic	*p*-Value	Post Hoc
Median Usability	4.67	4.5	4.0	H	.001	1>3*, 2>3*
Median Technology Acceptance	4.67	4.50	4.09	H	<.001	1>3*, 2>3*
Median Ease of Use	4.50	4.50	4.0	H	<.001	1>3*, 2>3*
Median Usefulness	4.67	4.67	4.0	H	.021	1>3*, 2>3*
Median Intent to Use	5.0	5.0	4.0	H	.028	-
*** p<.01**						

Post-hoc analyses found that overall technology acceptance was significantly better for holograms and 3DPDF compared to printed images (Table 11). Participants felt both holograms and 3DPDFs were easier to use than printed images. Participants rated the holograms as more useful study aids than printed images. Pairwise comparisons of intent to use did not reach statistical significance. There were no significant differences between the holograms and 3D PDF groups for any of the technology acceptance measures.

Table 11: Post Hoc Pairwise Comparisons

Measure	Mann-Whitney U	*p*-Value	Effect size (*r*)
Median Usability			
Holograms / Printed Images	1026.5	<.001*	.36
Holograms / 3D PDF	1627.5	.443	-
3D PDF / Printed Images	1265.5	.007*	.25
Median Technology Acceptance			
Holograms / Printed Images	966.5	<.001*	.37
Holograms / 3D PDF	1500.5	.246	-
3D PDF / Printed Images	1161	.008*	.24
Median Ease of Use			
Holograms / Printed Images	868.5	<.001*	.44
Holograms / 3D PDF	1410.5	.051	-
3D PDF / Printed Images	1172.5	.003*	.27
Median Usefulness			
Holograms / Printed Images	1307	.014*	.22
Holograms / 3D PDF	1614	.458	-
3D PDF / Printed Images	1405	.109	-
Median Intent to Use			
Holograms / Printed Images	1394	.021	-
Holograms / 3D PDF	1782.5	.906	-
3D PDF / Printed Images	1415	.028	-

Cognitive Load

Cognitive load was assessed to determine the amount of mental effort associated with studying with the visualization treatment. The NASA TLX was used, with a focus on the mental effort subcategory. The results were used to assess the following hypothesis:

Hypothesis 5: Using the holograms will result in lower levels of cognitive load compared to printed images and monoscopic computer models with kinetic depth effect.

Mental effort associated with studying cardiac anatomy was significantly affected by display modality ($H(3) = 11.60$, $p = .003$). Participants in the printed image treatment group (*Mdn.* = 6.0) reported significantly higher mental effort than both the hologram treatment (*Mdn.* = 4.0; U = 1225.5, p = .004, r = .27) and the 3DPDF treatment (*Mdn.* = 4.0; U = 1216.5, p = .003, r = .27). There was no significant difference in mental effort between the hologram and 3D PDF treatment groups.

Anatomical Knowledge Performance

Anatomical knowledge performance was assessed using the pre- and post-test instruments to verify the follow hypotheses.

Hypothesis 6: Students using holograms demonstrate improved gains in spatial anatomical knowledge based on post-test results, when compared with post-test results using printed images.

Hypothesis 7: Students using holograms demonstrate improved gains in spatial anatomical knowledge based on post-test results, when compared with post-test results using monoscopic computer models with kinetic depth effect.

As indicated in the two rows of Table 12, the pre-test confirmed lack of cardiac anatomy knowledge among the nursing students. Median scores and number of students passing the pre-test were statistically equivalent across treatment groups. As indicated in the post-test rows of Table 12, all within treatment post-test median scores and number of passing students demonstrated statistically significant improvements from pre-test performance ($p < .001$ for all treatments).

Table 12: Cardiac Anatomy Knowledge Performance Outcomes and Efficiency of Instructional Conditions

Measure	Holograms (1)	3D PDF (2)	Printed Images (3)	Between Groups *p*-Value	Pairwise Comparison
Pre-Test					
Median	33.3	40.0	33.3	.144	-
IQR	20.0 – 51.7	26.7 – 66.7	26.7 – 60.0		
Range	6.7 – 93.3	0.0 – 93.3	6.7 – 100.0		
Passing Students	6	12	10	.303	-
Post-Test					
Median	80.0	66.7	66.7	.008	1>2*, 1>3*
IQR	66.7 – 86.7	53.3 – 80.0	53.3 – 80.0		
Range	26.7 – 100.0	26.7 – 100.0	13.3 – 100.0		
Passing Students	41	26	25	.006	1>2*, 1>3*
Mental Effort					
Median	4.0	4.0	6.0	.003	1<3*, 2<3*
Mean	4.9	4.9	7.5		
SD	3.56	3.79	*4.9*		
Instructional Efficiency					
Mean	0.35	0.03	-0.36	.002	1>3*
SD	0.85	1.06	1.12		
p < .01					

Most importantly, Table 12 presents between treatment analysis indicating post-test performance (*H*(3) = 9.59; *p* = .008) and number of passing students ($\chi^2(2) = 10.375$, *p* = .006) was significantly affected by display modality. Pairwise comparisons revealed hologram scores were significantly higher compared to both printed image (*U* = 1262.5, p = .007, *r* = .25*)* and the 3DPDF scores (*U* = 1299.5, *p* = .008, *r* = .24). Figure 23 visually portrays the pre- and post-test performance across treatment groups. Due to the lack of normality of the post-test data, median is the primary reported metric; however, to be thorough, the averages for each group are shown in Figure 24.

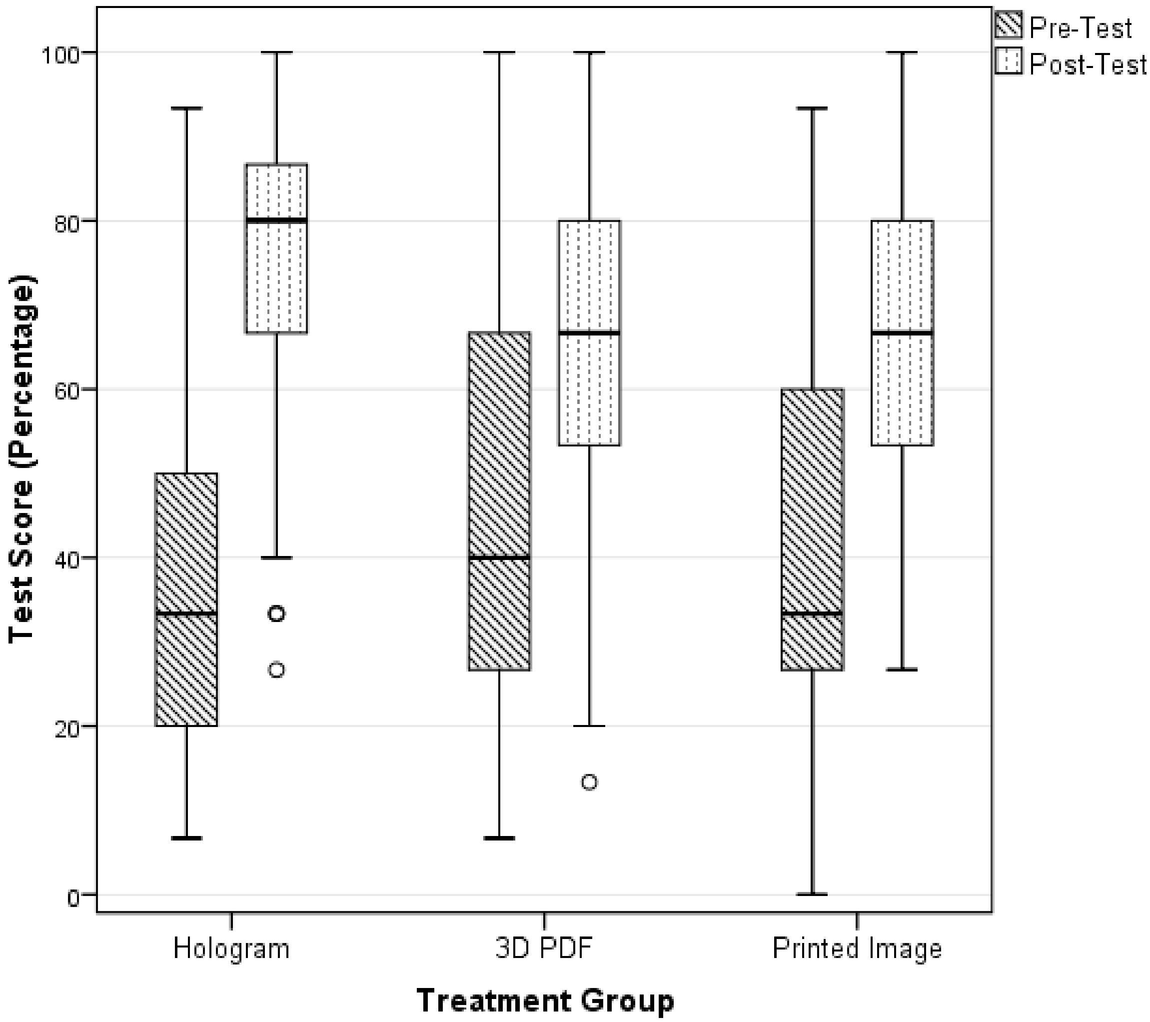


Figure 23: Box Plot of Pre- and Post-Test Scores Clustered by Treatment Group

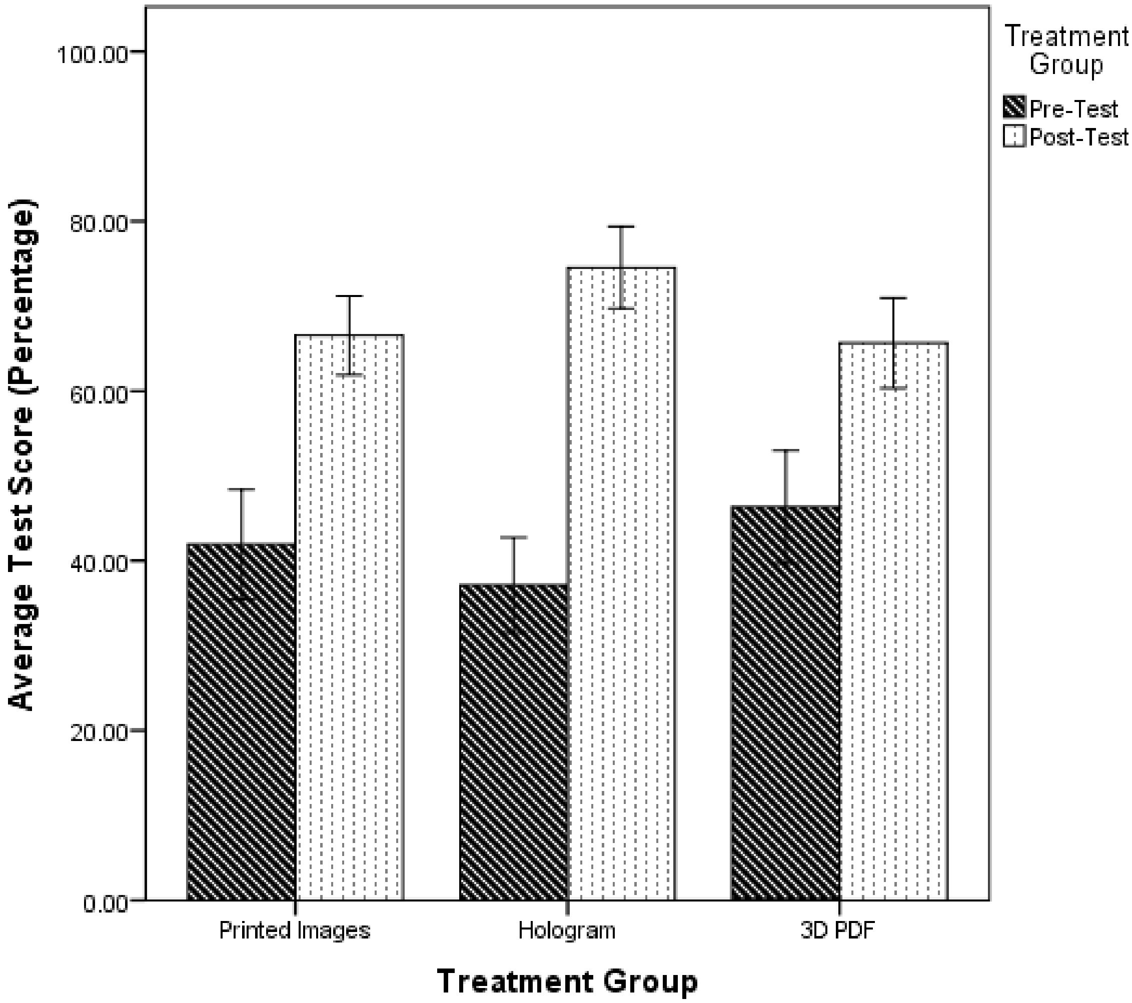


Figure 24: Bar Graph of Average Pre- and Post-Test Scores and Standard Deviation Clustered by Treatment Group

Continuing the performance analysis, the number of passing students in the hologram treatment was significantly higher compared to printed images ($\chi^2(1) = 8.12$, $p = .004$) and 3DPDFs ($\chi^2(1) = 7.60$, $p = .006$). When using holograms, the odds of a student passing the post-test was 2.84 times higher than students using 3DPDF, and 2.91 times higher than students using printed images, based on the odds ratio. There was no significant difference in post-test scores or number of passing students between the 3D PDF and printed images treatments.

Combining the aforementioned mental effort with knowledge performance, the efficiency of instructional condition was significantly different between treatments ($H(3) = 12.47$, $p < .01$) (Figure 25). Holograms were significantly more efficient than printed images ($U = 1115, p < .001$, $r = .31$). While noticeable, the difference between holograms and 3D PDF ($p = .097$) and between 3D PDF and printed images ($p = .051$) did not reach statistical significance.

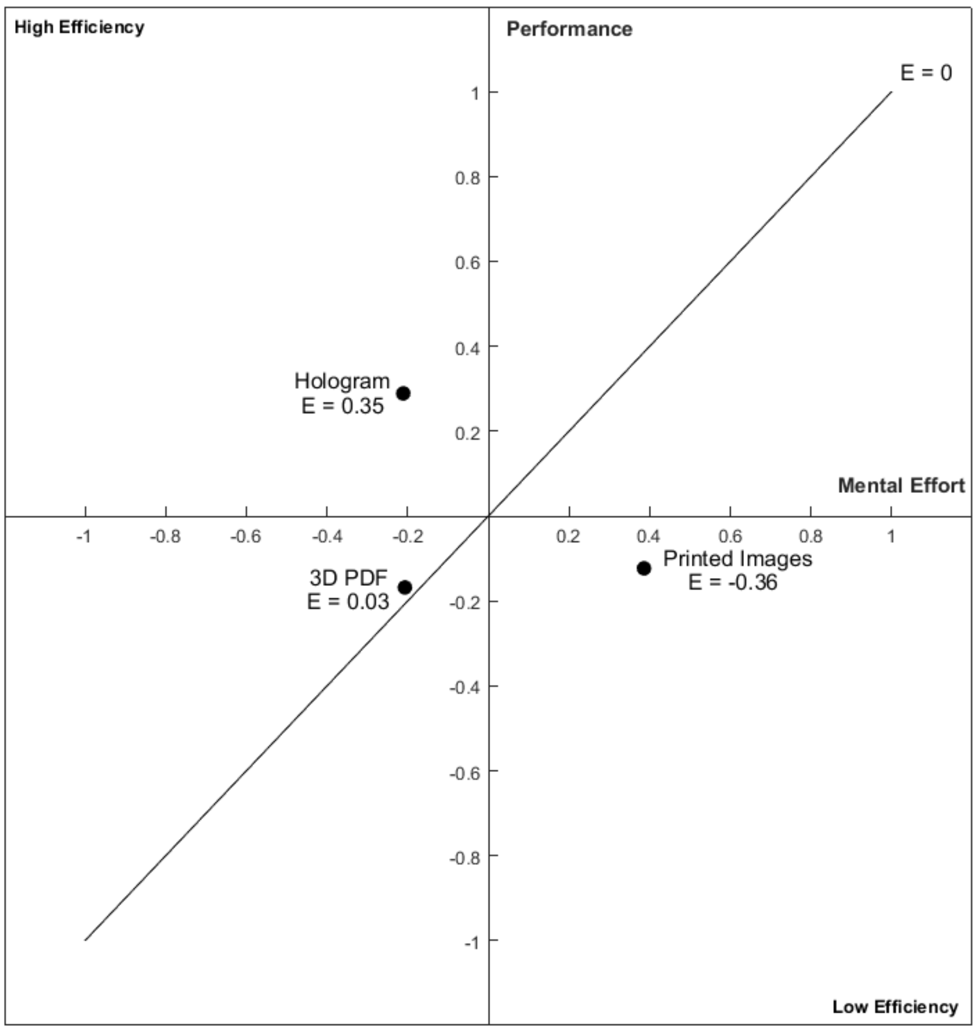


Figure 25: Efficiency of Hologram, 3DPDF, and Printed Image Conditions

Confidence

Confidence was measured in a single Likert-scale item at the end of the demographics survey and the end of the technology acceptance instrument. The scale ran from 1-7, with 1 representing very low confidence and 7 representing very high confidence in cardiac anatomy. The results from that item were used to assess the following hypothesis:

> *Hypothesis 8: Students using holograms will demonstrate improved ability to identify anatomical structures and nomenclature, compared to monoscopic 3D models with kinetic depth effect.*

The results of the confidence analysis showed improvement in confidence between pre- and post-study across each treatment group ($p < .001$ for each treatment) and the overall study population ($z = -9.68$, $p < .001$; $r = .73$). Pre-study confidence did not differ between treatment groups ($H(3) = 1.69$; $p = .431$). Post-study confidence was significantly different between treatment groups ($H(3) = 6.96$; $p = .031$). Pairwise analysis found that participants studying with holograms (*Mdn.* = 5) were significantly more confident than those using printed images (*Mdn.* = 5; $U = 1262.5$, $p = .007$, $r = .27$). In this comparison, the median confidence value is the same while the statistical test showed a significant difference; as such, additional values for mean and mean rank are included in Table 13. The differences in confidence between holograms and 3DPDF ($p = .11$) and between 3DPDF and printed images ($p = .38$) did not reach statistical significance.

Table 13: Pre- and Post-Study Anatomical Confidence Among Participants

Measure	Holograms (1)	3D PDF (2)	Printed Images (3)	Between Treatment Statistic	*p*-Value	Post Hoc
Pre-Study Confidence Median	3	3	4	H	.431	-
Post-Study Confidence Median	5	5	5	H	.031	1>3*
Post-Study Confidence Mean	5.23	4.82	4.71			
Post-Study Confidence Mean Rank	101.97	86.82	78.21			
*** $p < .01$**						

Visual Spatial Ability

Visual Spatial ability was assessed with two instruments: the paper-folding test and the card-rotation test.

Hypothesis 9: There is a relationship between an individual's VSA and their performance using holograms.

Hypothesis 10: Students with low VSA show larger improvements due to the addition of 3D holographic content compared to students with high VSA.

There was no meaningful relationship between learning gains or post-test performance and VSA for participants studying with holograms (Table 14). Strong correlations were found between post-test score and learning gain and between paper folding score and card rotation score.

Table 14: Correlation Between Knowledge Performance and Visual Spatial Ability

	Card Rotation Score	Paper Folding Score	Post Test Score	Learning Gain
Learning Gain	-.132	.018	.478*	1
Post Test Score	.116	.130	1	
Paper Folding Score	.522*	1		
Card Rotation Score	1			
p < .01				

Focusing on the knowledge performance of students with low visual-spatial ability, the learning gains (H(3) = 7.638, p = .022) and post-test performance (H(3) = 5.7, p = *.05)* differed significantly across treatment groups (Table 15). Post-hoc analysis found that the post test scores of low visual-spatial ability hologram participants (*Mdn.* = 73.3) showed improvement compared to low VSA participants using printed images (*Mdn.* = 60.0; U = 141.5, p = .029; r = .41) and near significance compared to 3DPDF (p = *.072).* Looking at learning gains, hologram participants showed a significantly larger learning gain (*Mdn* = 40.0) compared to 3DPDF (*Mdn.* = 10.0; U = 53, p = .007; r = .48).

Table 15: Comparison of Knowledge Performance Measures for Participants with Low Visual-Spatial Ability

Measure	Holograms (1)	3D PDF (2)	Printed Images (3)	Between Treatment Statistic	*p*-Value	Post Hoc
Median Post-Test Score	73.3	63.3	60.0	H	.05	1>3*
Median Learning Gains	40.0	10.0	33.3	H	.022	1>2*
***p* < .05**						

CHAPTER 5: SUMMARY OF FINDINGS, CONCLUSIONS, RESEARCH LIMITATIONS, AND FUTURE RESEARCH

Summary of Findings and Conclusions

Human anatomy is a complex subject, and many students struggle to learn and translate this knowledge to clinical care. Technological means have been used to address this problem, including 3D display technology; however, the vast majority of research has been conducted on monoscopic 3D displays. This research directly targets a gap in research related to autostereoscopic 3D displays and comparative study of 3D displays in anatomical education.

The experiment employed a randomized control-group study design with a control and two treatment groups. The control group received printed images, a monoscopic 3D treatment group received 3DPDF models via laptop computer with a traditional 2D display, and an autostereoscopic 3D treatment group received static holographic prints. The outcome measures included usability, technology acceptance, anatomical knowledge performance, cognitive load, confidence, and VSA.

Usability

The usability of the holograms was rated as quite high, with a median response of 4.67 out of 5, with higher scores indicating more positive response (H1). Participants rated the holograms significantly better in terms of usability than printed images (H2). There was not a statistically significant different between the reported usability of the holograms and 3D PDF (H3).

Technology Acceptance

Participants rated the holograms positively across all measures of technology acceptance on a scale from 1 (low) to 5 (high): ease of use (4.5), usefulness (4.67), intent to use (5.0) and overall technology acceptance (4.67) (H4). Comparing with the other treatment groups, both holograms and 3DPDF were rated significantly better than printed images in ease of use and overall technology acceptance. Holograms were rated significantly more useful than printed images. There were no differences in intent to use across the treatment groups.

The overall positive perceptions of the holographic technology in terms of both usability and technology acceptance suggest that the holograms were well-received and would likely be used if implemented into a curriculum. Furthermore, the holograms and the 3DPDF showed similar levels of user satisfaction and technology acceptance. The fact that the holograms, an unfamiliar technology, was able to show similar ease of use and usefulness to a technology as well-known as computer-based models, is very promising.

Cognitive Load

Participants self-reported their cognitive load immediately after studying with their treatment visualization, using the NASA-TLX with a scale from 1 (low) to 20 (high). The median cognitive load measures follow: holograms (4.0), 3DPDF (4.0), and printed images 6.0). Both the hologram treatment group and the 3DPDF treatment group reported significantly lower cognitive load than the printed images group (H5). There was no significant difference in reported cognitive load between the hologram and 3DPDF treatment groups.

Literature indicates that minimizing extraneous cognitive load, the portion of cognitive load induced by the presentation of the instructional material, enables improvements in learning processes (Mayer, 2002; J Sweller, 1994). In this study, lower mental effort was reported by the holographic and 3DPDF groups, indicating that these visualization techniques minimize extraneous cognitive load compared to printed images. Researchers hypothesize this change in cognitive load may result from additional 3D information in the hologram and 3DPDF presentations. These visualizations may promote the transformation of 2D and 3D thinking and reduce cognitive loads, a mechanism inferred by other researchers for subjects such as chemistry (Wu & Shah, 2004). Interestingly, 3DPDF resulted in similar cognitive load to holograms, despite having significantly lower post-test results. These findings tend to support the theory in the literature that a more efficient instructional medium, in this case holographic visualization, may result in decreased extraneous load while also optimizing germane cognitive load processes, such as the construction of schemas (Kirschner, 2002). This would result in a similar overall cognitive load for both visualizations, with holograms having a larger segment of germane load and thereby improved performance (J. J. Van Merriënboer & Sweller, 2010).

Anatomical Knowledge Performance

The results from the pre- and post-test were used to assess differences between the treatment groups regarding anatomical knowledge performance. There was no statistically significant difference between the pre-test scores across treatment groups. Additionally, there was not a significant difference in the number of students passing the pre-test across groups. Focusing on post-test performance, there was a significant affect from the treatment modality seen across treatment groups. The median post test scores follow: holograms (80.0), 3DPDF (66.7), and printed images (66.7). The hologram treatment group showed statistically significant improve in post-test performance compared to both the printed images (H6) and 3DPDF (H7) treatment groups. Furthermore, participants using the holograms treatment were significantly more likely to pass the post-test than participant using printed images or 3DPDFs. When using holograms, the odds of a student passing the post-test was 2.84 times higher than students using 3DPDF, and 2.91 times higher than students using printed images, based on the odds ratio.

Combining the performance data with cognitive load data, the efficiency of instructional condition was computer for each treatment: holograms (.35), 3DPDF (.03), and printed images (-.36). The holograms were a significantly more efficiency instructional condition compared to printed images. While noticeable, the differences between holograms and 3D PDF and between 3D PDF and printed images did not reach statistical significance.

These results indicate autostereoscopic holograms improve anatomical learning and reduce cognitive load of students. Specifically autostereoscopic holograms appear to impart spatial information more completely, as evidenced by improvements in post-test scores and number of students meeting minimum proficiency levels. This improvement appears caused by stereopsis, convergence, and motion parallax depth cues present with holographic visualization but not present in the printed image and monoscopic 3D treatments. This finding is in line with analyses across other domains, suggesting human performance when learning spatial relationships and recalling objects / scenes is heavily influenced by stereoscopic depth cues (McIntire et al., 2012).

Confidence

Participants reported their confidence in cardiac anatomy on a scale from 1 (very unconfident) to 7 (very confident), prior to and after the treatment study period. There was not a significant difference in reported confidence between the treatment groups on the pre-study confidence assessment. Following the study period, all treatment groups reported significant improvement in confidence. In the post-test confidence assessment, participants in the holograms group reported significantly higher confidence than the printed images group (H8). Comparisons between holograms and 3DPDF and between 3DPDF and printed images did not reach statistical significance.

The confidence findings suggest that studying with an autostereoscopic display gives students a better assurance of understanding the material. A less complete 3D representation of an object, such as printed images or a monoscopic 3D model, leaves room for a participant's visual system to reconstruct the image. This process may subconsciously trigger notions of potential errors in reconstruction, thereby reducing self-confidence in the source material. Additionally, the holograms group did perform better on post-tests, suggesting that students were accurate when assessing their confidence in cardiac anatomy.

Visual Spatial Ability

Visual spatial ability was assessed using the card rotation test and the paper folding test. There was not a significant correlation between the VSA scores and the post-test performance for the holograms treatment group (H9). The analysis then focused on students with low VSA, with the notion that 3D technology might be able to improve performance of low VSA. Low VSA participants in the holograms group scored significantly higher on the post-test than low VSA participants in the printed images group, and approached significance compared to the 3DPDF group. Looking at learning gains, the holograms group showed a significantly larger improvement than the 3DPDF group. These findings suggest that the holograms had significant effect on the low VSA students, improving their performance compared to other treatments.

Study Limitations

To begin, the study design had limitations. Since the post-test and study period were only separated by a short period of time, during which participants completed the NASA-TLX and technology acceptance instruments, the post-test performance measure is more akin to short-term recall than long-term knowledge gains. Additionally, related to the cognitive load outcome, the NASA-TLX instrument is a subjective measure of workload. Other measures of cognitive load, such as dual-task performance or brain activity (fMRI), would provide a more objective, direct metric(Brunken, Plass, & Leutner, 2003); however, these techniques are expensive and generally ill-suited for a classroom environment.

The subjects were not tested for stereopsis prior to enrollment in this study, such as the Frisby test(Tong et al., 2014). The study was limited in the amount of time with students, which required the elimination of certain tests, including stereopsis testing. While the data could provide interesting comparisons, the practical value was limited. In a real world scenario in which holograms were placed into an education setting, students would not be excluded due to a lack of stereopsis.

Future Research

This research establishes protocols and baseline outcomes that may be reused to investigate new display modalities. Due to sample size limitations, additional displays, such as stereoscopic 3D or autostereoscopic lenticular lens, could not be studied while maintaining statistically meaningful results. By reusing the protocols and baseline outcomes presented above, future research can expand the understanding of novel technology treatments without having to repeat past treatments. Considerations for future research include additional studies using 3DPDFs, such as the effect of touchscreen interaction on mental effort or displaying a 3DPDF using autostereoscopic 3D display devices such as lenticular displays. 3DPDFs are of particular interest because of the scalability of the format, the low cost per instance, and the ability accommodate various display technologies with a single, ubiquitous file format.

While not the primary focus of this dissertation, the area of augmented reality is certainly of great interest and importance in medical education. The combination of physical reality with augmented visual information provides strong depth cues with the benefit of virtual information. Comparing augmented reality with other 3D modalities is a largely unexplored domain.

Though autostereoscopic display technology is nascent, advances in the realm of holographic and volumetric displays (Smalley et al., 2018) are occurring rapidly. These displays would serve as an enabling technology for a vast array of medical education subjects: more immersive virtual patients; improved visualization during anatomical education or surgical planning; and even speculative topics such as telesurgery. Studies looking at task-based training applications, such as surgical or diagnostic skills, would be an important research avenue for autostereoscopic displays. For example, a comparative study between a 2D display, a stereoscopic display, and an autosteoscopic display for a virtual patient, to assess immersion and user performance would be very valuable.

In general, there still exists a significant gap in knowledge to determine the appropriate display modality for medical tasks. The popular notion is that display choice will be task dependent, with some tasks appropriate for 2D displays, while others might be best suited for stereoscopic, autostereoscopic, or augmented reality. Based on the rapid development of display technology and positive findings of this study, researchers believe additional research in autostereoscopic displays and comparative analyses between display technologies would benefit the medical community and numerous other communities which employ 3D visualization.

APPENDIX A: IRB APPROVAL

University of Central Florida Institutional Review Board
Office of Research & Commercialization
12201 Research Parkway, Suite 501
Orlando, Florida 32826-3246
Telephone: 407-823-2901, 407-882-2901 or 407-882-2276
www.research.ucf.edu/compliance/irb.html

Notice that UCF Relied Upon Other IRB for Review and Approval

From : **UCF Institutional Review Board**
FWA00000351, IRB00001138

To : **Matthew Hackett**

Date : **May 08, 2018**

IRB Number: **SBE-18-13719**

Study Title: **Analysis of Holographic and 3D Display Training Aids for Anatomy Education**

Dear Researcher:

The research protocol noted above was reviewed by an University of Central Florida IRB Designated Reviewer on 5/8/2018. The UCF IRB accepts the Army Research Lab's Institutional Review Board review and approval of this study for the protection of human subjects in research. **The expiration date was the date assigned by the ARL IRB and the consent process was the process approved by that IRB.**

UCF IRB clarifies that this Rely Upon request was submitted after the research was completed by the researcher and included an expired approval letter from ARL IRB. It is understood that the ARL IRB was the IRB of Record for this study and the ARL IRB approved the research protocol from December 2nd, 2016 to December 1st, 2017.

All data, including signed consent forms if applicable, must be retained and secured per protocol for a minimum of five years (six if HIPAA applies) past the completion of this research. Any links to the identification of participants should be maintained and secured per protocol. Additional requirements may be imposed by your funding agency, your department, or other entities. Access to data is limited to authorized individuals listed as key study personnel.

The UCF IRB acknowledges that the ARL coverage expired on December 1st, 2017. The researcher was informed by the ARL IRB that all research activities, including data analysis of personally identifiable information, must cease at the time of the email notice (December 4th, 2017). The study has been marked as expired in our records. If this study is funded by any branch of the Department of Health and Human Services (DHHS), an Office for Human Research Protections (OHRP) IRB Authorization form must be signed by the signatory officials of both institutions and a copy of the form must be kept on file at the IRB office of both institutions.

This letter is signed by:

Signature applied by Jennifer Neal-Jimenez on 05/08/2018 03:02:12 PM EDT

Designated Reviewer

DEPARTMENT OF THE ARMY
U.S. ARMY RESEARCH, DEVELOPMENT AND ENGINEERING COMMAND
ARMY RESEARCH LABORATORY
ABERDEEN PROVING GROUND MD 21005-5067

REPLY TO
ATTENTION TO

RDRL-HR 2 Dec 2016

MEMORANDUM FOR: Matthew Hackett, ARL-HRED, Orlando, FL

FROM: Daniel Cassenti, ARL IRB

SUBJECT: Approval of Research Study, ARL 16-111

Project Title: Analysis of Holographic and 3D Display Training Aids for Anatomy Education
Submission Type: Initial Protocol
Approval Period: 2 December 2016 to 1 December 2017

The purpose of this memorandum is to notify you that the research project identified above was determined to be minimal risk and has been approved by the ARL Institutional Review Board (IRB) by expedited review under category 7 on 2 Dec 2016.

The project documents were initially reviewed on 22 Nov 2016:

- Protocol cover sheet
- Protocol
- Consent
- 3 Scientific Reviews
- Memo addressing the scientific reviewers comments
- Recruitment Flyer
- CV, CITI, COI for the PI

The IRB reviewer requested changes in order to secure approval. On 2 Dec 2016 the following modified documents were reviewed and the study was approved:

- Memo addressing the reviewers comments
- Revised protocol (received 1 Dec 2016)
- Revised consent (received 1 Dec 2016)
- Revised recruitment flyer

RDRL-HR
Subject: Approval of Research Study, ARL 16-111

As principal investigator, you are responsible for ensuring that the study is conducted in accordance with the final version of your protocol. You cannot delegate your supervisory responsibility to anyone else associated with the project. If you leave the project a new principal investigator should be designated for the research. Designation of a new principal investigator should be reported to the IRB.

In addition, you must report the following to the IRB:

- You must report changes in research personnel, including the principal investigator, involved in the study.
- You must report changes in the research procedures before they are initiated. You can report minor changes by completing the ARL amendment form.
- You may make changes in research procedures implemented to eliminate immediate hazards to the subjects, but they must be reported within 10 days of their implementation on the amendment form.
- You must report completion or discontinuation of your study by submitting a completion or discontinuation report to the IRB.
- You must report plans to continue your study beyond the expiration date before you attain that date, by submission of a continuing review form 30 days before the expiration date.
- You must promptly report any injury or Unanticipated Problems Involving Risks to Participants or Others (UPIRTSO) to the IRB within 24 hours (via phone message, e-mail, or written report) of the incident. This should be followed by a full written report within 10 business days.

A UPIRTSO is defined in DODI 3216.02, Glossary as "Any incident, experience, or outcome that meets ALL three of the following conditions:

- Is unexpected (in terms of nature, severity, or frequency) given the procedures described in the research protocol documents (e.g., the IRB-approved research protocol and informed consent document) and the characteristics of the human subject population being studied.
- Is related or possibly related to participation in the research. *Possibly related* means there is a reasonable likelihood that the incident, experience, or outcome may have been caused by the procedures involved in the research.
- Suggests that the research places human subjects or others at a greater risk of harm (including physical, psychological, economic, or social harm) than was previously known or recognized, even if no harm has actually occurred.

RDRL-HR
Subject: Approval of Research Study, ARL 16-111

The ARL IRB approved consent form, dated 2 Dec 2016, is included with this correspondence. Use this version when consenting subjects for your study.

Good luck with your research.

CASSENTI.DANIEL.N.1276013528 Digitally signed by CASSENTI.DANIEL.N.1276013528
DN: c=US, o=U.S. Government, ou=DoD, ou=PKI, ou=USA, cn=CASSENTI.DANIEL.N.1276013528
Date: 2016.12.02 15:00:06 -05'00'

DANIEL CASSENTI
ARL IRB Co-Chair

STAFFING/ROUTING HISTORY	TRACKING NUMBER GEARS-355123	DATE STARTED 2017-01-19	SUSPENSE 2017-01-27 Time Sensitive? ☐
ORGANIZATION B/187	PACKET TYPE Actions	ACTION OFFICER/POC Long, Robert P II LTC USARMY MEDCOM AMEDDCS (US)	

SUBJECT

68C Hologram Project

DISCUSSION/ADDITIONAL INFORMATION

Research protocol submitted by Mr. Matthew Hackett of the Army Research Laboratory Orlando, Florida. Project will test the new 68C students' learning. Three cohorts of roughly 75 students (will not impact POI) will be administered a pre-test and then given traditional paper and pencil instruction, Surface tablet instruction or 3-D hologram instruction. The post-test will then be administered. Outcome variable of best teaching modality will be determined. We will defer to the Army Research Laboratory Institutional Review Board as the IRB on record.

RECOMMENDATION

This is a win-win for the AMEDDC&S. We get to explore teaching using tablet and holographic devices. Mr. Hackett is willing to share all data with the AMEDDC&S for future studies looking into tablet-based and alternative methods of instruction/learning.

ENCLOSURES

ARL 16-111 IRB Approved ICF_Hackett_Hologram_2016_HC.pdf
RESEARCH PROTOCOL Hackett_Holograms_SanAntonio.docx

STAFF ROUTING APPROVAL

OFFICE	NAME	DATE	DECISION/RECOMMENDATION
	Drennon, William Scott COL USARMY MEDCOM ACADEMY BDE (US)	2017-01-20	Approve
	Peacock, Tanya A COL USARMY MEDCOM AMEDDCS (US)	2017-01-21	Reassign action
	Marshall, Christopher R SGM USARMY MEDCOM AMEDDCS HRCOE (US)	2017-01-23	Approve
	Long, Robert P II LTC USARMY MEDCOM AMEDDCS (US)	2017-01-24	Approve

REVIEWER COMMENTS

Drennon, William Scott COL USARMY MEDCOM ACADEMY BDE (US) (2017-01-20): Concur!

Peacock, Tanya A COL USARMY MEDCOM AMEDDCS (US) (2017-01-21): SGM Marshall - As previously discussed. Please provide input and route to Dr. Bowman after you provide your comments. Thanks.

Marshall, Christopher R SGM USARMY MEDCOM AMEDDCS HRCOE (US) (2017-01-23): I assume that the protocol will be for the 68C students and not DCMT as it is written here. I am curious of the results.

APPENDIX B: USABILITY / TECHNOLOGY ACCEPTANCE INSTRUMENT

Participant ID: Hologram

	Totally Agree 1	2	3	4	Totally Disagree 5
I would enjoy using the holograms to study.					
I found the holograms easy to study with.					
I imagine most people would learn to use the holograms quickly.					
I found the holograms unnecessarily complex to use.					
I felt confident using the holograms to study.					
I needed to learn a lot of things before I could begin studying using the holograms.					
The anatomical views using the holograms are clear and understandable.					
Interacting with the hologram does not require a lot of my mental effort.					
Using the holograms improves my performance when learning anatomy.					
Using the holograms increases my anatomical knowledge.					
I find the holograms useful when learning anatomy.					
Assuming I have access to anatomical holograms, I predict that I would use them.					

Please rate your current confidence in cardiac anatomy:						
1 Very Unconfident	2 Unconfident	3 Somewhat Unconfident	4 Neutral	5 Somewhat Confident	6 Confident	7 Very Confident

APPENDIX C: NASA TLX COGNITIVE LOAD INSTRUMENT

Participant ID:

Mental Demand — How mentally demanding was the task?

Very Low — Very High

Physical Demand — How physically demanding was the task?

Very Low — Very High

Temporal Demand — How hurried or rushed was the pace of the task?

Very Low — Very High

Performance — How successful were you in accomplishing what you were asked to do?

Perfect — Failure

Effort — How hard did you have to work to accomplish your level of performance?

Very Low — Very High

Frustration — How insecure, discouraged, irritated, stressed, and annoyed wereyou?

Very Low — Very High

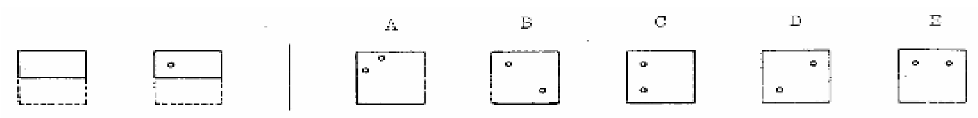
APPENDIX D: VZ-2 VISUALIZATION INSTRUMENTS

Name / ID: ______________________________________

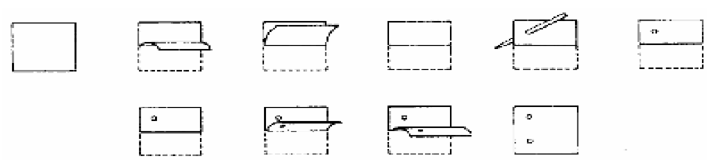
Paper Folding Test – VZ-2

In this test you are to imagine the folding and unfolding of pieces of paper. In each problem in the test there are some figures drawn at the left of a vertical line and there are others drawn at the right of the line. The figures at the represent a square piece of paper being folded, and the last of these figures has one or two small circles drawn on it to show where the paper has been punched. Each hole is punched through all the thicknesses of paper at that point. One of the five figures at the right of the vertical line shows where the holes will be when the paper is completely unfolded. You are to decide which one of these figures is correct and draw an X through that figure.

Now try the sample problem below.
(In this problem only one hole was punched in the folded paper.)



The correct answer to the sample problem above is C and so it should have been marked with an X. The figures below show how the paper was folded and why C is the correct answer.



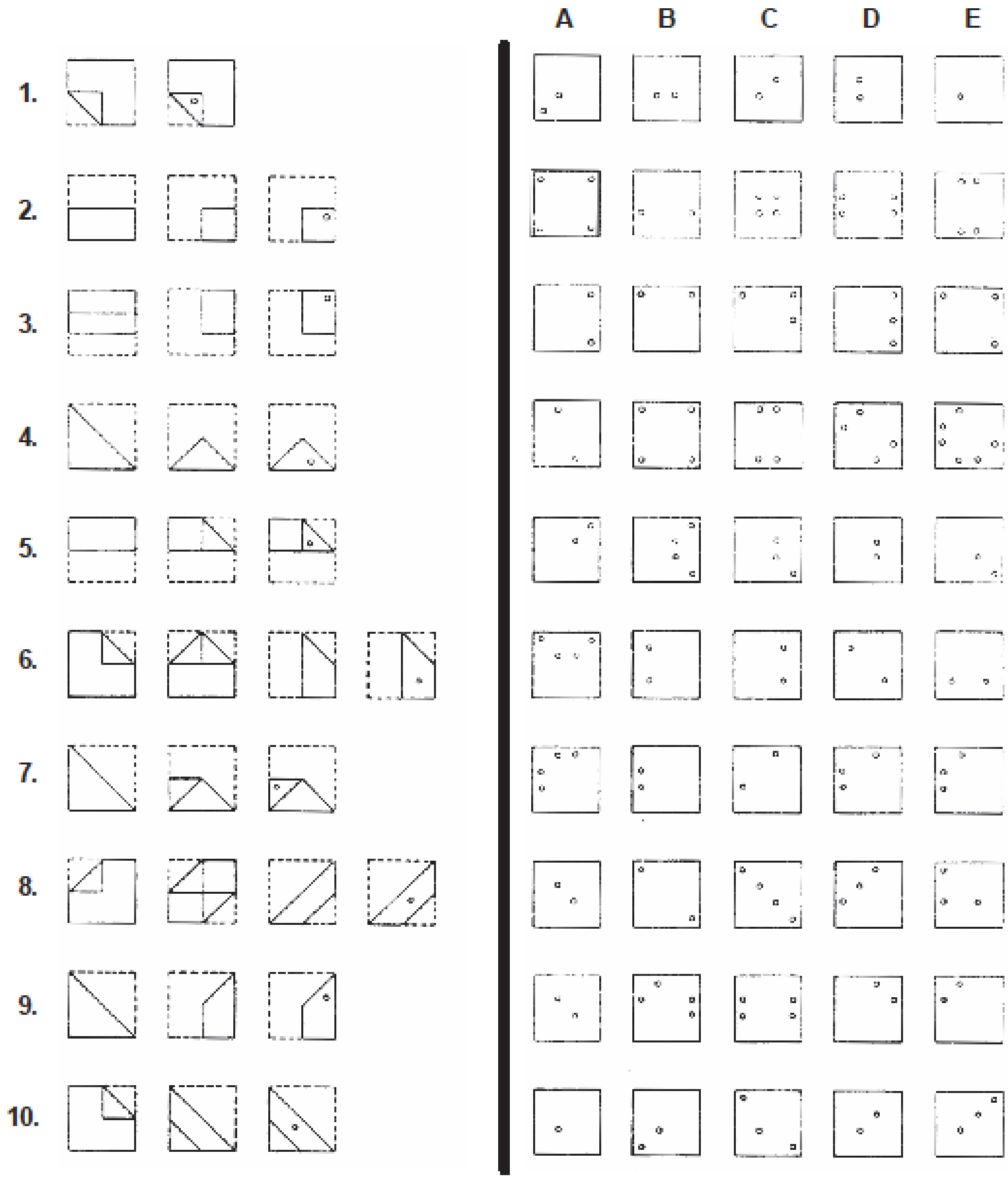
In these problems all of the folds that are made are shown in the figures at the left of the line, and the paper is not turned or moved in any way except to make the folds shown in the figures. Remember, the correct answer is the figure that shows the positions of the holes when the paper is completely unfolded.

Your score on this test will be the number marked correctly minus a fraction of the number marked incorrectly. Therefore, it will not be to your advantage to guess unless you are able to eliminate one or more of the answer choices as wrong.

You will have 3 minutes for each of the two parts of this test. Each part has 1 page. When you have finished Part 1, STOP. Please do not go on to Part 2 until you are asked to do so.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO.

Part 1 (3 minutes)

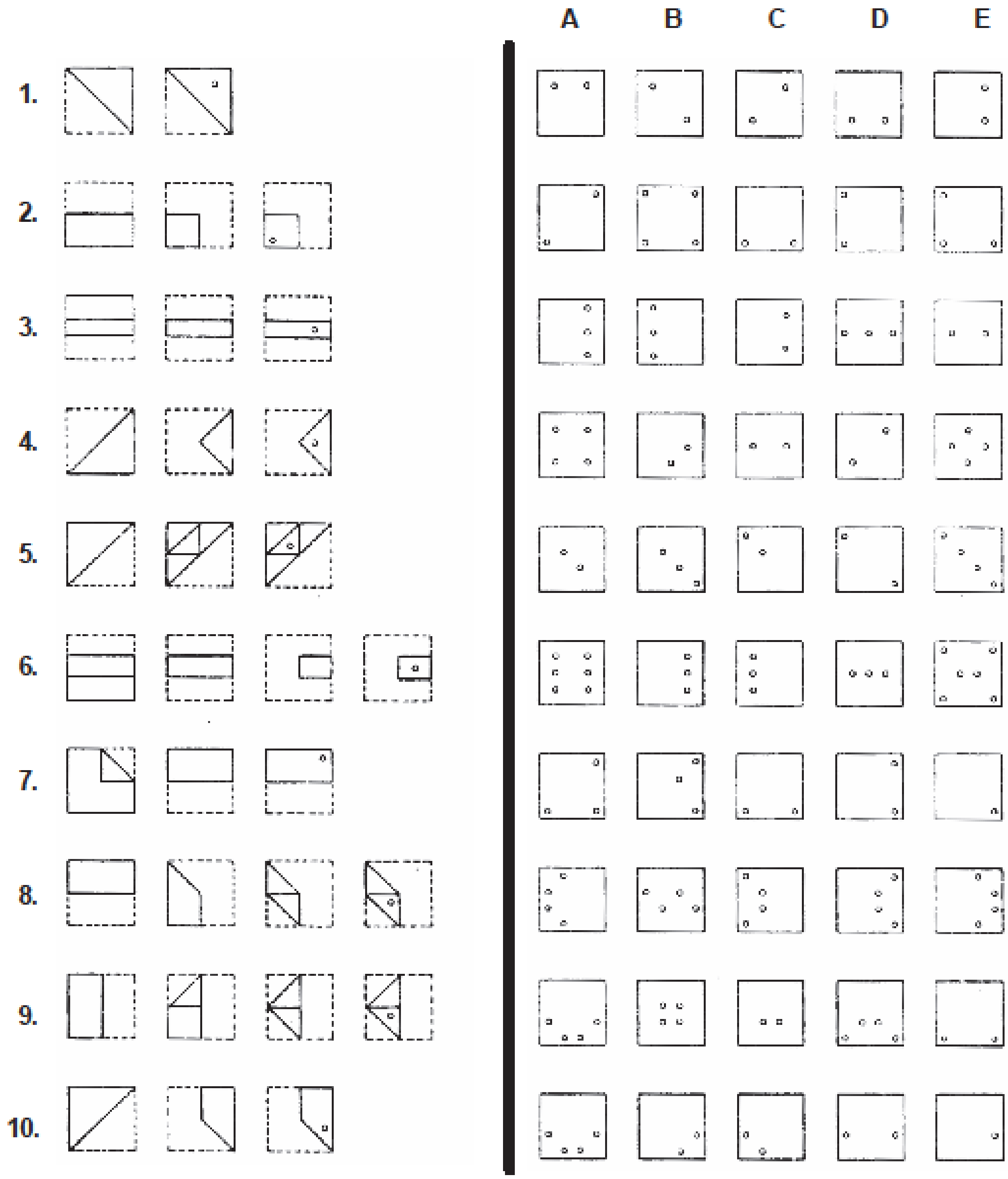


DO NOT GO ON TO THE NEXT PAGE UNTIL ASKED TO DO SO.

STOP.

VZ-2

Part 1 (3 minutes)



DO NOT GO BACK TO PART 1, AND

DO NOT GO ON TO THE NEXT PAGE UNTIL ASKED TO DO SO.

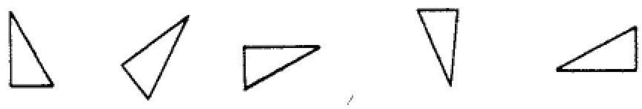
STOP.

APPENDIX E: CARD ROTATIONS TEST

Participant ID:

CARD ROTATIONS TEST — S-1 (Rev.)

This is a test of your ability to see differences in figures. Look at the 5 triangle-shaped cards drawn below.



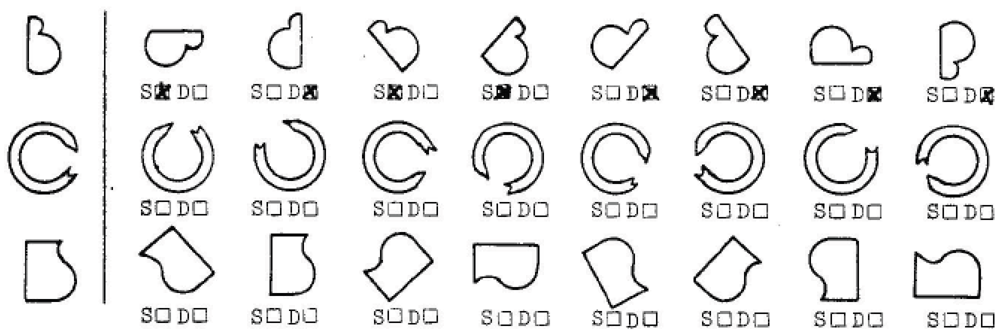
All of these drawings are of the same card, which has been slid around into different positions on the page.

Now look at the 2 cards below:

These two cards are not alike. The first cannot be made to look like the second by sliding it around on the page. It would have to be flipped over or made differently.

Each problem in this test consists of one card on the left of a vertical line and eight cards on the right. You are to decide whether each of the eight cards on the right is the same as or different from the card at the left. Mark the box beside the S if it is the same as the one at the beginning of the row. Mark the box beside the D if it is different from the one at the beginning of the row.

Practice on the following rows. The first row has been correctly marked for you.

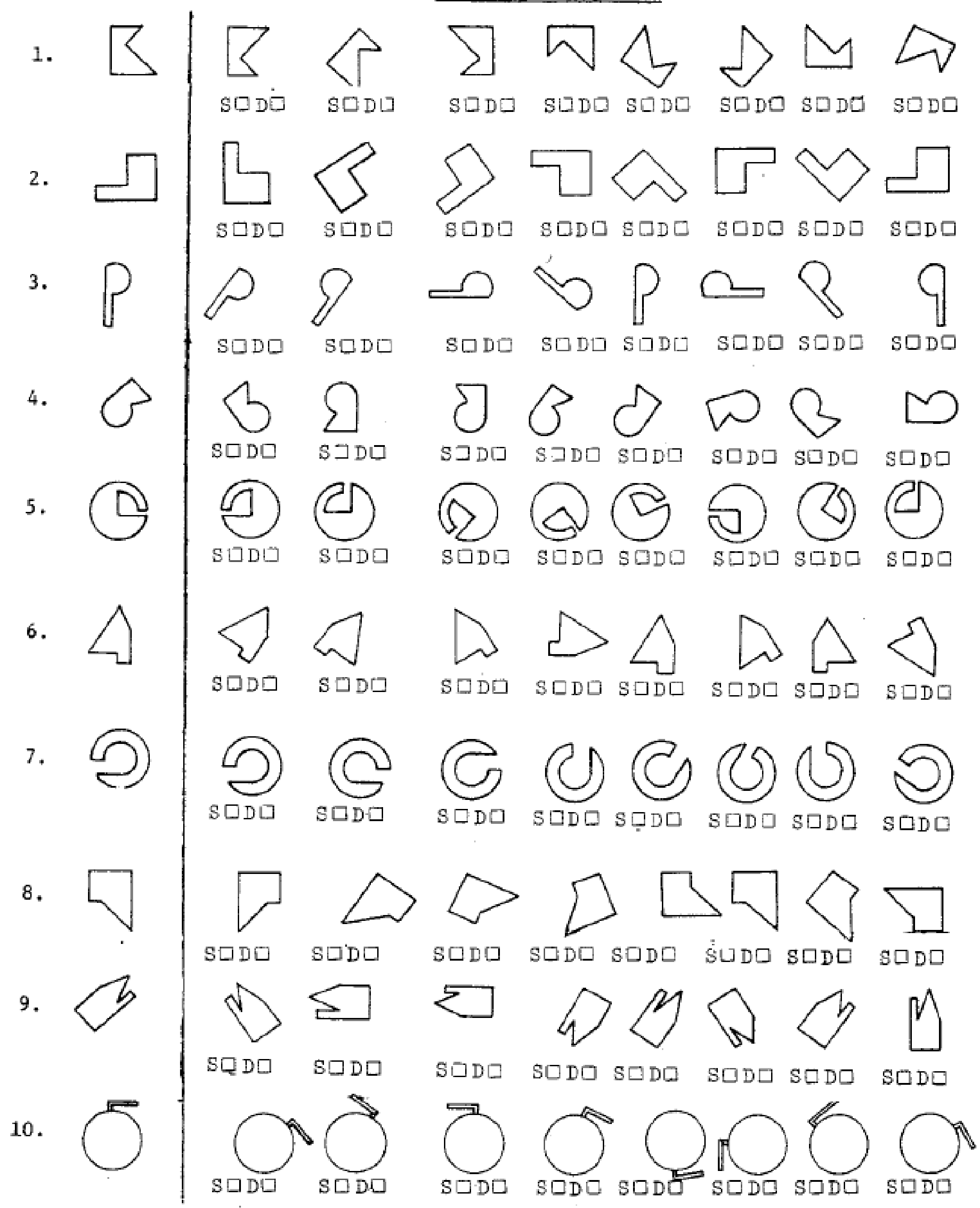


Your score on this test will be the number of items answered correctly minus the number answered incorrectly. Therefore, it will not be to your advantage to guess, unless you have some idea whether the card is the same or different. Work as quickly as you can without sacrificing accuracy.

You will have 3 minutes for each of the two parts of this test. Each part has 1 page. When you have finished Part 1, STOP. Please do not go on to Part 2 until you are asked to do so.

DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO.

Part 1 (3 minutes)



DO NOT TURN THIS PAGE UNTIL ASKED TO DO SO.

STOP.

APPENDIX F: DEMOGRAPHICS

PARTICIPANT NUMBER		
AGE		
GENDER		
DOMINANT HAND (CIRCLE ONE)	LEFT	RIGHT

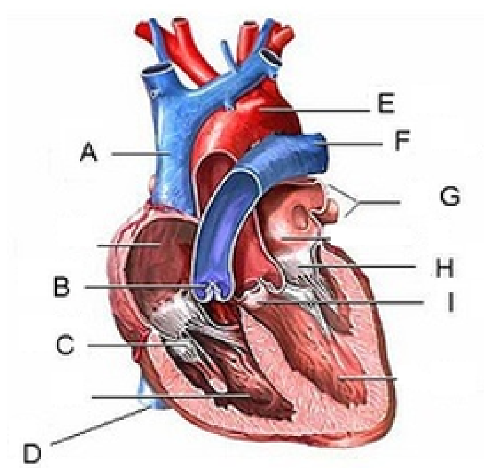
Please rate your current confidence in cardiac anatomy:						
1 Very Unconfident	2 Unconfident	3 Somewhat Unconfident	4 Neutral	5 Somewhat Confident	6 Confident	7 Very Confident

APPENDIX G: ANATOMY PRE- AND POST-TEST

1. What is the valve between the pulmonary artery and the heart?
    a. Mitral
    b. Aortic
    c. Pulmonary
    d. Tricuspid
2. The two largest veins leading to the heart are the:
    a. Pulmonary veins
    b. Internal and external iliac vein
    c. Hepatic veins
    d. Inferior and superior vena cava
3. All of the following vessels lie superior to (above) the heart except:
    a. Superior vena cava
    b. Aorta
    c. Inferior vena cava
    d. Pulmonary artery
4. Which of the following contains de-oxygenated (blue) blood?
    a. Aorta
    b. Pulmonary artery
    c. Pulmonary veins
    d. Subclavian artery
5. How many cusps (flaps) does the pulmonary valve have?
    a. One
    b. Two
    c. Three
    d. Four
6. What is the largest vessel carrying oxygenated (red) blood from the heart?
    a. Aorta
    b. Pulmonary artery
    c. Pulmonary veins
    d. Superior vena cava

Match the anatomical structure with the corresponding location on the figure below:

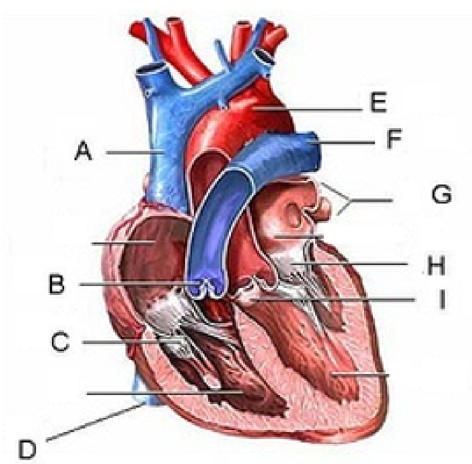
7. Aorta ____
8. Pulmonary Artery ____
9. Pulmonary Veins ____
10. Inferior Vena Cava ____
11. Superior Vena Cava ____
12. Mitral (bicuspid) valve ____
13. Aortic semi-lunar valve ____
14. Pulmonary semi-lunar valve ____
15. Tricuspid valve ____



1. How many cusps (flaps) does the pulmonary valve have?
    a. One
    b. Two
    c. Three
    d. Four
2. What is the largest vessel carrying oxygenated (red) blood from the heart?
    a. Aorta
    b. Pulmonary artery
    c. Pulmonary veins
    d. Superior vena cava
3. Which of the following contains de-oxygenated (blue) blood?
    a. Aorta
    b. Pulmonary artery
    c. Pulmonary veins
    d. Subclavian artery
4. The two largest veins leading to the heart are the:
    a. Pulmonary veins
    b. Internal and external iliac vein
    c. Hepatic veins
    d. Inferior and superior vena cava
5. What is the valve between the pulmonary artery and the heart?
    a. Mitral
    b. Aortic
    c. Pulmonary
    d. Tricuspid
6. All of the following vessels lie superior to (above) the heart except:
    a. Superior vena cava
    b. Aorta
    c. Inferior vena cava
    d. Pulmonary artery

Match the anatomical structure with the corresponding location on the figure below:

7. Aorta ____
8. Pulmonary Artery ____
9. Pulmonary Veins ____
10. Inferior Vena Cava ____
11. Superior Vena Cava ____
12. Mitral (bicuspid) valve ____
13. Aortic semi-lunar valve ____
14. Pulmonary semi-lunar valve ____
15. Tricuspid valve ____



LIST OF REFERENCES

Abildgaard, A., Witwit, A. K., Karlsen, J. S., Jacobsen, E. A., Tennøe, B., Ringstad, G., & Due-Tønnessen, P. (2010). An autostereoscopic 3D display can improve visualization of 3D models from intracranial MR angiography. *International Journal of Computer Assisted Radiology and Surgery, 5*(5), 549-554. doi:10.1007/s11548-010-0509-5

Abraham, B. (2013). A swept-volume 3D display: open sourcing 3D display technology with a modular, low cost design.

Abran, A., Khelifi, A., Suryn, W., & Seffah, A. (2003). Usability Meanings and Interpretations in ISO Standards. *Software Quality Journal, 11*(4), 325-338. doi:10.1023/A:1025869312943

Al-Khalili, S. M., & Coppoc, G. L. (2014). 2D and 3D Stereoscopic Videos Used as Pre-Anatomy Lab Tools Improve Students' Examination Performance in a Veterinary Gross Anatomy Course. *Journal of Veterinary Medical Education, 41*(1), 68-76. doi:10.3138/jvme.0613-082R

Albert, W., & Tullis, T. (2013). *Measuring the user experience: collecting, analyzing, and presenting usability metrics*: Newnes.

Allen, J. P. (2005). *The art of medicine in ancient Egypt*: Metropolitan Museum of Art.

Ames Jr, A. (1951). Visual perception and the rotating trapezoidal window. *Psychological Monographs: General and Applied, 65*(7), i.

Army, D. o. t. (2009). STP 8-68W13-SM-TG: APRIL 2009 -

SOLDIER’S MANUAL AND TRAINER’S GUIDE: MOS 68W.

Associated-Press. (2009). U.S. Military ER in Baghdad Handed Back to Iraq.

ATP 4-02.5. (2013).

Ayres, P. (2006). Using subjective measures to detect variations of intrinsic cognitive load within problems. *Learning and Instruction, 16*(5), 389-400.

Balogh, A., Preul, M. C., Schornak, M., Hickman, M., & Spetzler, R. F. (2004). Intraoperative stereoscopic QuickTime Virtual Reality. *Journal of Neurosurgery, 100*(4), 591-596. doi:doi:10.3171/jns.2004.100.4.0591

Bangor, A., Kortum, P. T., & Miller, J. T. (2008). An Empirical Evaluation of the System Usability Scale. *International Journal of Human-Computer Interaction, 24*(6), 574-594. doi:10.1080/10447310802205776

Battulga, B., Konishi, T., Tamura, Y., & Moriguchi, H. (2012). The effectiveness of an interactive 3-dimensional computer graphics model for medical education. *Interact J Med Res, 1*(2), e2. doi:10.2196/ijmr.2172

Beermann, J., Tetzlaff, R., Bruckner, T., Schoebinger, M., Muller-Stich, B. P., Gutt, C. N., . . . Fischer, L. (2010). Three-dimensional visualisation improves understanding of surgical liver anatomy. *Medical Education, 44*(9), 936-940. doi:10.1111/j.1365-2923.2010.03742.x

Benton, S. A., & Bove Jr, V. M. (2008). *Holographic imaging*: John Wiley & Sons.

Bergman, E. M., Prince, K. J., Drukker, J., van der Vleuten, C. P., & Scherpbier, A. J. (2008). How much anatomy is enough? *Anat Sci Educ, 1*(4), 184-188. doi:10.1002/ase.35

Berryman, D. R. (2012). Augmented reality: a review. *Med Ref Serv Q, 31*(2), 212-218. doi:10.1080/02763869.2012.670604

Bhangu, A., Boutefnouchet, T., Yong, X., Abrahams, P., & Joplin, R. (2010). A three-year prospective longitudinal cohort study of medical students' attitudes toward anatomy teaching and their career aspirations. *Anatomical Sciences Education, 3*(4), 184-190. doi:10.1002/ase.165

Blum, T., Kleeberger, V., Bichlmeier, C., & Navab, N. (2012). mirracle: An augmented reality magic mirror system for anatomy education. *Virtual Reality Short Papers and Posters (VRW), 2012 IEEE*, 115-116. doi:10.1109/VR.2012.6180909

Bogue, B., & Marra, R. (2003). Visual Spatial Skills. *AWE Research Overview Suite*.

Botha, C. P., Preim, B., Kaufman, A., Takahashi, S., & Ynnerman, A. (2014). From individual to population: Challenges in Medical Visualization *Scientific Visualization* (pp. 265-282): Springer.

Boylan, M. (2005). Hippocrates (c. 450–c. 380 BCE). *Internet Encyclopedia of Philosophy*.

Brenton, H., Hernandez, J., Bello, F., Strutton, P., Purkayastha, S., Firth, T., & Darzi, A. (2007). Using multimedia and Web3D to enhance anatomy teaching. *Computers & Education, 49*(1), 32-53. doi:10.1016/j.compedu.2005.06.005

Brotherton-Ratcliffe, D., Zacharovas, S. J., Bakanas, R. J., Pileckas, J., Nikolskij, A., & Kuchin, J. (2011). Digital holographic printing using pulsed RGB lasers. *Optical Engineering, 50*(9), 091307-091307-091309. doi:10.1117/1.3596182

Brown, P. M., Hamilton, N. M., & Denison, A. R. (2012). A novel 3D stereoscopic anatomy tutorial. *Clin Teach, 9*(1), 50-53. doi:10.1111/j.1743-498X.2011.00488.x

Brunken, R., Plass, J. L., & Leutner, D. (2003). Direct measurement of cognitive load in multimedia learning. *Educational Psychologist, 38*(1), 53-61.

Bushberg, J. T., & Boone, J. M. (2011). *The essential physics of medical imaging*: Lippincott Williams & Wilkins.

Carroll, J. B. (1993). *Human Cognitive Abilities*: Cambridge University Press.

Castellano, J. A. (2012). *Handbook of display technology*: Elsevier.

Castiglione, A. (1941). *The origin and development of the anatomical theater to the end of the Renaissance.* Paper presented at the Ciba Symposia.

Chi, M. T., Feltovich, P. J., & Glaser, R. (1981). Categorization and representation of physics problems by experts and novices. *Cognitive Science, 5*(2), 121-152.

Chien, C.-H., Chen, C.-H., & Jeng, T.-S. (2010). *An interactive augmented reality system for learning anatomy structure.* Paper presented at the Proceedings of the International MultiConference of Engineers and Computer Scientists.

Cho, J. H., Bass, M., & Jenssen, H. P. (2007). Volumetric three-dimensional up-conversion display medium. *Journal of the Society for Information Display, 15*(12), 1029-1036.

Christopher, L. A., William, A., & Cohen-Gadol, A. A. (2013). Future Directions in 3-Dimensional Imaging and Neurosurgery: Stereoscopy and Autostereoscopy. *Neurosurgery, 72*, A131-A138. doi:10.1227/NEU.0b013e318270d9c0

Chu, J. C. H., Gong, X., Cai, Y., Kirk, M. C., Zusag, T. W., Shott, S., . . . Abrams, R. A. (2009). Application of holographic display in radiotherapy treatment planning II: a multi-institutional study. *Journal of Applied Clinical Medical Physics, 10*(3), 115-124. doi:10.1120/jacmp.v10i3.2902

Codd, A. M., & Choudhury, B. (2011). Virtual Reality Anatomy: Is it Comparable with Traditional Methods in the Teaching of Human Forearm Musculoskeletal Anatomy? *Anatomical Sciences Education, 4*(3), 119-125. doi:10.1002/ase.214

Cohen, J. (1992). A power primer. *Psychological bulletin, 112*(1), 155.

Cottam, W. W. (1999). Adequacy of medical school gross anatomy education as perceived by certain postgraduate residency programs and anatomy course directors. *Clinical Anatomy, 12*(1), 55-65.

Dare, A. O., & Grand, W. Neurosurgical anatomy laboratory: Suggested guide for neurosurgeons in training.

Davis, F. D. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. *MIS quarterly, 13*(3), 319-340. doi:10.2307/249008

Davis, F. D. (1989). Perceived usefulness, perceived ease of use, and user acceptance of information technology. *MIS quarterly*, 319-340.

Davis, F. D., Bagozzi, R. P., & Warshaw, P. R. (1989). User Acceptance of Computer Technology: A Comparison of Two Theoretical Models. *Management science, 35*(8), 982-1003. doi:doi:10.1287/mnsc.35.8.982

Davis, L., Hamza-Lup, F. G., Daly, J., Ha, Y., Frolich, S., Meyer, C., . . . Rolland, J. P. (2002). *Application of augmented reality to visualizing anatomical airways.* Paper presented at the Head-Mounted Displays VII.

De Zwart, S., IJzerman, W., Dekker, T., & Wolter, W. (2004). *A 20-in. switchable auto-stereoscopic 2D/3D display.* Paper presented at the Proceedings of International Display Workshops (Society for Information Display, 2004).

Derrickson, B., & Tortora, G. J. (2006). Principles of anatomy and physiology: Willely, ISBN: 0-471-71871-8. pp.

Dodgson, N. A. (2005). Autostereoscopic 3D displays. *Computer*(8), 31-36. doi:10.1109/MC.2005.252

Drukker, J., Van Mameren, H., Croonen, H., Wanders, A., Verwijnen, G., & Van Der Vleuten, C. (1999). Het oordeel van artsen over het door hen genoten anatomieonderwijs. [Physicians' retrospective evaluation of anatomy teaching.] *Bull Med Onderwijs, 18*, 9-16.

Duckworth, W. L. H., Lyons, M. C., & Towers, B. (1962). *Galen on anatomical procedures*: University Press.

ECMA. (2007). Universal 3D File Format.

EMT-Training. (2008). The Human Body.

Estevez, M. E., Lindgren, K. A., & Bergethon, P. R. (2010). A Novel Three-Dimensional Tool for Teaching Human Neuroanatomy. *Anatomical Sciences Education, 3*(6), 309-317. doi:10.1002/ase.186

Favalora, G. E. (2005). Volumetric 3D displays and application infrastructure. *Computer, 38*(8), 37-+. doi:10.1109/mc.2005.276

FDA, F. a. D. A. (2014). Fluoroscopy.

Ferrer-Torregrosa, J., Torralba, J., Jimenez, M. A., García, S., & Barcia, J. M. (2014). ARBOOK: Development and Assessment of a Tool Based on Augmented Reality for Anatomy. *Journal of Science Education and Technology, 24*(1), 119-124. doi:10.1007/s10956-014-9526-4

Fitzgerald, J., White, M., Tang, S., Maxwell-Armstrong, C., & James, D. (2008). Are we teaching sufficient anatomy at medical school? The opinions of newly qualified doctors. *Clinical Anatomy, 21*(7), 718-724.

Foo, J. L., Martinez-Escobar, M., Juhnke, B., Cassidy, K., Hisley, K., Lobe, T., & Winer, E. (2013). Evaluating Mental Workload of Two-Dimensional and Three-Dimensional Visualization for Anatomical Structure Localization. *Journal of Laparoendoscopic & Advanced Surgical Techniques, 23*(1), 65-70. doi:10.1089/lap.2012.0150

Frasca, D., Malezieux, R., Mertens, P., Neidhardt, J. P., & Voiglio, E. J. (2000). Review and evaluation of anatomy sites on the Internet (updated 1999). *Surgical and Radiologic Anatomy, 22*(2), 107-110. doi:10.1007/s00276-000-0107-2

Friedl, R., Preisack, M. B., Klas, W., Rose, T., Stracke, S., Quast, K. J., . . . Godje, O. (2002). Virtual reality and 3D visualizations in heart surgery education. *Heart Surg Forum, 5*(3), E17-21. Retrieved from

Friendly, M., & Denis, D. (2012). Milestone in the History of Thematic Cartography, Statistical Graphics, and Data Visualization.

Fuhrmann, S., Smith, N. J., Holzbach, M., & Nichols, T. (2009). Investigating Geospatial Holograms for Special Weapons and Tactics Teams. *Cartographic Perspectives*(63), 5-19. doi:10.14714/CP63.156

Gabor, D. (1948). A new microscopic principle. *Nature, 161*(4098), 777-778.

Gallo, L., & Ciampi, M. (2009). Wii Remote-enhanced Hand-Computer interaction for 3D medical image analysis. *Proceedings from Current Trends in Information Technology (CTIT),* 1-6. Retrieved from doi:10.1109/CTIT.2009.5423137

Gallo, L., De Pietro, G., Coronato, A., & Marra, I. (2008). Toward a natural interface to virtual medical imaging environments. *Proceedings of the working conference on Advanced visual interfaces*, 429-432. Retrieved from doi:10.1145/1385569.1385651

Garg, A., Norman, G. R., Spero, L., & Maheshwari, P. (1999). Do virtual computer models hinder anatomy learning? *Academic Medicine, 74*(10), S87-89. Retrieved from

Garg, A. X., Norman, G., & Sperotable, L. (2001). How medical students learn spatial anatomy. *The Lancet, 357*(9253), 363-364. doi:10.1016/S0140-6736(00)03649-7

Garg, G. N., Lawrence Spero, Ian Taylor, Amit. (1999). Learning anatomy: do new computer models improve spatial understanding? *Medical Teacher, 21*(5), 519-522. doi:10.1080/01421599979239

Gately, M., Zhai, Y., Yeary, M., Petrich, E., & Sawalha, L. (2011). A three-dimensional swept volume display based on LED arrays. *Journal of Display Technology, 7*(9), 503-514. doi:10.1109/JDT.2011.2157455

Geng, J. (2013). Three-dimensional display technologies. *Advances in Optics and Photonics, 5*(4), 456-535. doi:10.1364/AOP.5.000456

Gest, T. R., Burkel, W. E., & Cortright, G. W. (2009). A need for logical and consistent anatomical nomenclature for cutaneous nerves of the limbs. *Anatomical Sciences Education, 2*(3), 126-134.

Ghalioungui, P. (1963). Magic and Medical Science in Ancient Egypt.

Gorman, P. J., Meier, A. H., Rawn, C., & Krummel, T. M. (2000). The future of medical education is no longer blood and guts, it is bits and bytes. *American Journal of Surgery, 180*(5), 353-356. doi:10.1016/s0002-9610(00)00514-6

Gray, H. (1918). *Anatomy of the human body*: Lea & Febiger.

Guillot, A., Champely, S., Batier, C., Thiriet, P., & Collet, C. (2007). Relationship between spatial abilities, mental rotation and functional anatomy learning. *Advances in Health Sciences Education, 12*(4), 491-507. doi:10.1007/s10459-006-9021-7

Gupta, Y., Morgan, M., Singh, A., & Ellis, H. (2008). Junior doctors' knowledge of applied clinical anatomy. *Clinical Anatomy, 21*(4), 334-338. doi:10.1002/ca.20628

Hackett, M. (2013). *Medical Holography for Basic Anatomy Training*. Paper presented at the The Interservice/Industry Training, Simulation & Education Conference.

Hackett, M., & Fefferman, K. (2014). *Comparative Analysis of Holographic Display and Three-Dimensional Television.* Paper presented at the The Interservice/Industry Training, Simulation & Education Conference.

Hall, G. E., Loucks, S. F., Rutherford, W. L., & Newlove, B. W. (1975). Levels of use of the innovation: A framework for analyzing innovation adoption. *Journal of teacher education, 26*(1), 52-56. doi:10.1177/002248717502600114

Halle, M. (2005). *Autostereoscopic displays and computer graphics.* Paper presented at the ACM SIGGRAPH 2005.

Hariri, S., Rawn, C., Srivastava, S., Youngblood, P., & Ladd, A. (2004). Evaluation of a surgical simulator for learning clinical anatomy. *Medical Education, 38*(8), 896-902. doi:10.1111/j.1365-2929.2004.01897.x

Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in psychology, 52*, 139-183.

Hatzivassiliou, E. (1997). *Britain and the International Status of Cyprus, 1955-59*: University of Minnesota, Modern Greek Studies.

Hegarty, M., Keehner, M., Cohen, C., Montello, D. R., & Lippa, Y. (2007). The role of spatial cognition in medicine: Applications for selecting and training professionals. *Applied spatial cognition*, 285-315.

Hilbelink, A. J. (2009). A measure of the effectiveness of incorporating 3D human anatomy into an online undergraduate laboratory. *British Journal of Educational Technology, 40*(4), 664-672. doi:10.1111/j.1467-8535.2008.00886.x

Hoffman, D. M., Girshick, A. R., Akeley, K., & Banks, M. S. (2008). Vergence–accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of vision, 8*(3), 33.

Hoffman, H. M., Murray, M., Irwin, A. E., & McCracken, T. (1996). Developing a virtual reality-multimedia system for anatomy training. *Studies in health technology and informatics*, 204-210. doi:10.3233/978-1-60750-873-1-204

Hong, J., Kim, Y., Choi, H.-J., Hahn, J., Park, J.-H., Kim, H., . . . Lee, B. (2011). Three-dimensional display technologies of recent interest: principles, status, and issues [Invited]. *Applied optics, 50*(34), H87-H115. doi:10.1364/AO.50.000H87

Hoyek, N., Collet, C., Di Rienzo, F., De Almeida, M., & Guillot, A. (2014). Effectiveness of three-dimensional digital animation in teaching human anatomy in an authentic classroom context. *Anatomical Sciences Education, 7*(6), 430-437. doi:10.1002/ase.1446

Hoyek, N., Collet, C., Rastello, O., Fargier, P., Thiriet, P., & Guillot, A. (2009). Enhancement of Mental Rotation Abilities and Its Effect on Anatomy Learning. *Teaching and Learning in Medicine, 21*(3), 201-206. doi:10.1080/10401330903014178

Hu, A., Wilson, T., Ladak, H., Haase, P., Doyle, P., & Fung, K. (2010). Evaluation of a Three-Dimensional Educational Computer Model of the Larynx: Voicing a New Direction. *Journal of Otolaryngology-Head & Neck Surgery, 39*(3), 315-322. doi:10.2310/7070.2010.090074

Huang, H.-M., Liaw, S.-S., & Lai, C.-M. (2013). Exploring learner acceptance of the use of virtual reality in medical education: a case study of desktop and projection-based display systems. *Interactive Learning Environments*, 1-17. doi:10.1080/10494820.2013.817436

Ilgner, J. F. R., Kawai, T., Shibata, T., Yamazoe, T., & Westhofen, M. (2006). *Evaluation of stereoscopic medical video content on an autostereoscopic display for undergraduate medical education.* Paper presented at the Proceedings SPIE Stereoscopic Displays and Virtual Reality Systems XIII.

Inoue, T., & Ohzu, H. (1997). Accommodative responses to stereoscopic three-dimensional display. *Applied optics, 36*(19), 4509-4515. doi:10.1364/AO.36.004509

Jaffar, A. A. (2012). YouTube: An emerging tool in anatomy education. *Anatomical Sciences Education, 5*(3), 158-164. doi:10.1002/ase.1268

Jezzard, P., Matthews, P. M., & Smith, S. M. (2001). *Functional MRI: an introduction to methods* (Vol. 3): Oxford university press Oxford.

Jones, A., McDowall, I., Yamada, H., Bolas, M., & Debevec, P. (2007). Rendering for an interactive 360 light field display. *ACM Transactions on Graphics (TOG), 26*(3), 40. doi:10.1145/1276377.1276427

Juanes, J. A., Hernández, D., Ruisoto, P., García, E., Villarrubia, G., & Prats, A. (2014). *Augmented reality techniques, using mobile devices, for learning human anatomy*. Paper presented at the Proceedings of the Second International Conference on Technological Ecosystems for Enhancing Multiculturality.

Jurgaitis, J., Paskonis, M., Pivoriunas, J., Martinaityte, I., Juska, A., Jurgaitiene, R., . . . Schemmer, P. (2008). The comparison of 2-dimensional with 3-dimensional hepatic visualization in the clinical hepatic anatomy education. *Medicina (Kaunas), 44*(6), 428-438. doi:10.1.1.596.9576

Kachlik, D., Baca, V., Bozdechova, I., Cech, P., & Musil, V. (2008). Anatomical terminology and nomenclature: past, present and highlights. *Surgical and Radiologic Anatomy, 30*(6), 459-466. doi:10.1007/s00276-008-0357-y

Kalloniatis, M., & Luu, C. (2007). Perceptions of Depth. *http://webvision.med.utah.edu/book/part-viii-gabac-receptors/perception-of-depth/*.

Kamphuis, C., Barsom, E., Schijven, M., & Christoph, N. (2014). Augmented reality in medical education? *Perspectives on Medical Education, 3*(4), 300-311. doi:10.1007/s40037-013-0107-7

Kancherla, A. R., Rolland, J. P., Wright, D. L., & Burdea, G. (1995). *A novel virtual reality tool for teaching dynamic 3D anatomy*. Paper presented at the Computer Vision, Virtual Reality and Robotics in Medicine.

Kassam, K. S., Markey, A. R., Cherkassky, V. L., Loewenstein, G., & Just, M. A. (2013). Identifying Emotions on the Basis of Neural Activation. *PLoS ONE, 8*(6), e66032. doi:10.1371/journal.pone.0066032

Keedy, A. W., Durack, J. C., Sandhu, P., Chen, E. M., O'Sullivan, P. S., & Breiman, R. S. (2011). Comparison of Traditional Methods with 3D Computer Models in the Instruction of Hepatobiliary Anatomy. *Anatomical Sciences Education, 4*(2), 84-91. doi:10.1002/ase.212

Khalil, M. K., Paas, F., Johnson, T. E., & Payer, A. F. (2005). Interactive and dynamic visualizations in teaching and learning of anatomy: A cognitive load perspective. *The Anatomical Record Part B: The New Anatomist, 286*(1), 8-14. doi:10.1002/ar.b.20077

Khan, J. (2014). BIOMEDICAL IMAGING: 3D digital holograms visualize biomedical applications. Retrieved from Laser Focus World website: http://www.laserfocusworld.com/index.html

Khan, J., Can, C., Greenaway, A., & Underwood, I. (2013). *A real-space interactive holographic display based on a large-aperture HOE.* Paper presented at the SPIE OPTO.

Kim, Y., Hong, K., & Lee, B. (2010). Recent researches based on integral imaging display method. *3D Research, 1*(1), 17-27. doi:10.1007/3DRes.01(2010)2

Kimura, H., Uchiyama, T., & Yoshikawa, H. (2006). *Laser produced 3D display in the air*. Paper presented at the ACM SIGGRAPH 2006 Emerging technologies.

Kirschner, P. A. (2002). Cognitive load theory: implications of cognitive load theory on the design of learning. *Learning and Instruction, 12*(1), 1-10. doi:https://doi.org/10.1016/S0959-4752(01)00014-7

Klug, M., Burnett, T., Fancello, A., Heath, A., Gardner, K., O'Connell, S., & Newswanger, C. (2013). *32.4: A Scalable, Collaborative, Interactive Light-field Display System.* Paper presented at the SID Symposium.

Klug, M., Holzbach, M., & Ferdman, A. (2001). Method and apparatus for recording one-step, full-color, full-parallax, holographic stereograms: Google Patents.

Kockro, R. A., Amaxopoulou, C., Killeen, T., Wagner, W., Reisch, R., Schwandt, E., . . . Stadie, A. T. (2015). Stereoscopic neuroanatomy lectures using a three-dimensional virtual reality environment. *Annals of Anatomy - Anatomischer Anzeiger, 201*, 91-98. doi:10.1016/j.aanat.2015.05.006

Kockro, R. A., & Hwang, P. Y. (2009). Virtual temporal bone: an interactive 3-dimensional learning aid for cranial base surgery. *Neurosurgery, 64*(5 Suppl 2), 216-229; discussion 229-230. doi:10.1227/01.neu.0000343744.46080.91

Kooi, F. L., & Toet, A. (2004). Visual comfort of binocular and 3D displays. *Displays, 25*(2–3), 99-108. doi:10.1016/j.displa.2004.07.004

Lang, U., Kieferle, J., & Wössner, U. (2003). *3D Visualization and Animation–An Introduction.* Paper presented at the Photogrammetric Week.

Langhans, K., Guill, C., Rieper, E., Oltmann, K., & Bahr, D. (2003). *Solid Felix: a static volume 3D-laser display.* Paper presented at the Electronic Imaging 2003.

Langlois, J., Wells, G. A., Lecourtois, M., Bergeron, G., Yetisir, E., & Martin, M. (2009). Spatial Abilities in an Elective Course of Applied Anatomy After a Problem-Based Learning Curriculum. *Anatomical Sciences Education, 2*(3), 107-112. doi:10.1002/ase.84

Lazarus, M. D., Chinchilli, V. M., Leong, S. L., & Kauffman, G. L. (2012). Perceptions of anatomy: Critical components in the clinical setting. *Anatomical Sciences Education, 5*(4), 187-199. doi:10.1002/ase.1281

Leith, E. N., & Upatnieks, J. (1962). Reconstructed wavefronts and communication theory. *JOSA, 52*(10), 1123-1128.

Leung, H., Lee, H., Mark, K., & Lui, K. M. (2012). *Unlocking the secret of 3D content for education.* Paper presented at the Teaching, Assessment and Learning for Engineering (TALE) 2012.

Lewin, S. (2014). Holographic displays coming to smartphones [News]. *Spectrum, IEEE, 51*(8), 13-14. doi:10.1109/MSPEC.2014.6866424

Lewis, T., Burnett, B., Tunstall, R., & Abrahams, P. (2014). Complementing anatomy education using three-dimensional anatomy mobile software applications on tablet computers. *Clinical Anatomy, 27*(3), 313-320. doi:10.1002/ca.22256

Li, Q., Ran, X., Zhang, S., Tan, L., & Qiu, M. (2014). A Digital Interactive Human Brain Atlas Based on Chinese Visible Human Datasets for Anatomy Teaching. *Journal of Craniofacial Surgery, 25*(1), 303-307. doi:10.1097/SCS.0b013e3182a4c54a

Likert, R. (1932). A technique for the measurement of attitudes. *Archives of psychology*.

Linn, M. C., & Petersen, A. C. (1985). Emergence and Characterization of Sex Differences in Spatial Ability: A Meta-Analysis. *Child Development, 56*(6), 1479-1498. doi:10.2307/1130467

Liu, K., Fang, B., Wu, Y., Li, Y., Jin, J., Tan, L., & Zhang, S. (2013). Anatomical education and surgical simulation based on the Chinese Visible Human: a three-dimensional virtual model of the larynx region. *Anatomical Science International, 88*(4), 254-258. doi:10.1007/s12565-013-0186-x

Luursema, J.-M., Verwey, W. B., Kommers, P. A. M., & Annema, J.-H. (2008). The role of stereopsis in virtual anatomical learning. *Interacting with Computers, 20*(4-5), 455-460. doi:10.1016/j.intcom.2008.04.003

Luursema, J.-M., Verwey, W. B., Kommers, P. A. M., Geelkerken, R. H., & Vos, H. J. (2006). Optimizing conditions for computer-assisted anatomical learning. *Interacting with Computers, 18*(5), 1123-1138. doi:10.1016/j.intcom.2006.01.005

Martinez-Cuenca, R., Saavedra, G., Martinez-Corral, M., & Javidi, B. (2009). Progress in 3-D multiperspective display by integral imaging. *Proceedings of the Ieee, 97*(6), 1067-1077.

Mayer, R. E. (2002). Multimedia learning. *Psychology of Learning and Motivation, 41*, 85-139.

Mayer, R. E. (2005). *The Cambridge handbook of multimedia learning*: Cambridge university press.

McCracken, H. (2015). Oculus Rift Vs. HoloLens: Will The Digital-Reality Revolution Be Virtual Or Augmented? Retrieved from http://www.fastcompany.com/3048633/facebook-vs-microsoft-will-the-digital-reality-revolution-be-virtual-or-augmented

McIntire, J. P., Havig, P. R., & Geiselman, E. E. (2012). *What is 3D good for? A review of human performance on stereoscopic 3D displays.* Paper presented at the SPIE Defense, Security, and Sensing.

McLachlan, J. C., Bligh, J., Bradley, P., & Searle, J. (2004). Teaching anatomy without cadavers. *Medical Education, 38*(4), 418-424. doi:10.1046/j.1365-2923.2004.01795.x

McLuhan, M. (2011). *The Gutenberg galaxy: The making of typographic man*: University of Toronto Press.

Meng, M., Fallavollita, P., Blum, T., Eck, U., Sandor, C., Weidert, S., . . . Navab, N. (2013). *Kinect for interactive AR anatomy learning.* Paper presented at the 2013 IEEE International Symposium on Mixed and Augmented Reality (ISMAR).

Metzler, R., Stein, D., Tetzlaff, R., Bruckner, T., Meinzer, H. P., Buchler, M. W., . . . Fischer, L. (2012). Teaching on three-dimensional presentation does not improve the understanding of according CT images: a randomized controlled study. *Teach Learn Med, 24*(2), 140-148. doi:10.1080/10401334.2012.664963

Miller, G. A. (1956). The magical number seven, plus or minus two: some limits on our capacity for processing information. *Psychological review, 63*(2), 81.

Montomery, T. (2014). Anatomy, Physiology, and Pathology of the Human Eye.

Muller-Stich, B. P., Lob, N., Wald, D., Bruckner, T., Meinzer, H. P., Kadmon, M., . . . Fischer, L. (2013). Regular three-dimensional presentations improve in the identification of surgical liver anatomy - a randomized study. *BMC Med Educ, 13*, 131. doi:10.1186/1472-6920-13-131

Newe, A. (2015). Towards an easier creation of three-dimensional data for embedding into scholarly 3D PDF (Portable Document Format) files. *PeerJ, 3*, e794. doi:10.7717/peerj.794

NHTSA. (2009). Emergency Medical Services: Education Agenda for the Future.

Nicholson, D. T., Chalk, C., Funnell, W. R. J., & Daniel, S. J. (2006). Can virtual reality improve anatomy education? A randomised controlled study of a computer-generated three-dimensional anatomical ear model. *Medical Education, 40*(11), 1081-1087. doi:10.1111/j.1365-2929.2006.02611.x

Nieder, G. L., Nagy, F., Pearson, J. C., & Wagner, L. A. (2002). *QuickTime VR Anatomical Resource: A Library of Virtual Anatomical Objects for Gross Anatomy Educators*. Paper presented at the 6th Annual Meeting of the International Association of Medical Science Educators.

Nieder, G. L., Scott, J. N., & Anderson, M. D. (2000). Using QuickTime virtual reality objects in computer-assisted instruction of gross anatomy: Yorick—the VR Skull. *Clinical Anatomy, 13*(4), 287-293. doi:10.1002/1098-2353(2000)13:4<287::AID-CA9>3.0.CO;2-L

Nobuoka, D., Fuji, T., Yoshida, K., Takagi, K., Kuise, T., Utsumi, M., . . . Ohtsuka, A. (2014). Surgical education using a multi-viewpoint and multi-layer three-dimensional atlas of surgical anatomy. *Journal of Hepato-Biliary-Pancreatic Sciences, 21*(8), 556-561. doi:10.1002/jhbp.108

Noguera, J. M., Jimenez, J. J., & Osuna-Perez, M. C. (2013). Development and evaluation of a 3D mobile application for learning manual therapy in the physiotherapy laboratory. *Computers & Education, 69*, 96-108. doi:10.1016/j.compedu.2013.07.007

Nutton, V. (1984). From Galen to Alexander, aspects of medicine and medical practice in late Antiquity. *Dumbarton Oaks Papers*, 1-14.

Osler, W. (1921). *Evolution of modern medicine*: DevCom.

Paas, F., Tuovinen, J. E., Tabbers, H., & Van Gerven, P. W. M. (2003). Cognitive load measurement as a means to advance cognitive load theory. *Educational Psychologist, 38*(1), 63-71. doi:10.1207/s15326985ep3801_8

Paas, F. G., & Van Merriënboer, J. J. (1993). The efficiency of instructional conditions: An approach to combine mental effort and performance measures. *Human Factors: The Journal of the Human Factors and Ergonomics Society, 35*(4), 737-743.

Pandey, P., & Zimitat, C. (2007). Medical students' learning of anatomy: memorisation, understanding and visualisation. *Medical Education*, *41*(1), 7-14. doi:10.1111/j.1365-2929.2006.02643.x

Park, J. S., Chung, M. S., Hwang, S. B., Lee, Y. S., Har, D.-H., & Park, H. S. (2005). Visible Korean human: improved serially sectioned images of the entire body. *Medical Imaging, IEEE Transactions on*, *24*(3), 352-360. doi:10.1109/TMI.2004.842454

Pastoor, S., & Wöpking, M. (1997). 3-D displays: A review of current technologies. *Displays, 17*(2), 100-110. doi:10.1016/S0141-9382(96)01040-2

Petersson, H., Sinkvist, D., Wang, C. L., & Smedby, O. (2009). Web-Based Interactive 3D Visualization as a Tool for Improved Anatomy Learning. *Anatomical Sciences Education, 2*(2), 61-68. doi:10.1002/ase.76

Pfautz, J. D. (2000). *Depth perception in computer graphics.* University of Cambridge.

Phelps, A., Naeger, D. M., & Marcovici, P. (2012). Embedding 3D radiology models in portable document format. *American Journal of Roentgenology, 199*(6).

Porter, R. (1999). *The Greatest Benefit to Mankind: A Medical History of Humanity (The Norton History of Science)*: WW Norton & Company.

Portoni, L., Patak, A., Noirard, P., Grossetie, J.-C., & van Berkel, C. (2000). *Real-time auto-stereoscopic visualization of 3D medical images.* Paper presented at the Medical Imaging 2000.

Prince, K. A. H., van de Wiel, M., Scherpbier, A. J. A., can der Vleuten, C. M., & Boshuizen, H. A. (2000). A Qualitative Analysis of the Transition from Theory to Practice in Undergraduate Training in a PBL-Medical School. *Advances in Health Sciences Education, 5*(2), 105-116. doi:10.1023/A:1009873003677

Prince, K. J. A. H., Van Mameren, H., Hylkema, N., Drukker, J., Scherpbier, A. J. J. A., & Van Der Vleuten, C. P. M. (2003). Does problem-based learning lead to deficiencies in basic science knowledge? An empirical case on anatomy. *Medical Education, 37*(1), 15-21. doi:10.1046/j.1365-2923.2003.01402.x

Qualter, J., Sculli, F., Oliker, A., Napier, Z., Lee, S., Garcia, J., . . . Triola, M. (2011). The biodigital human: a web-based 3D platform for medical visualization and education. *Studies in health technology and informatics, 173*, 359-361. doi:10.3233/978-1-61499-022-2-359

Ranschaert, E. (2010). Zerker's Diverticulum.

Rasimah, C. M. Y., Ahmad, A., & Zaman, H. B. (2011). Evaluation of user acceptance of mixed reality technology. *Australasian Journal of Educational Technology, 27*(8), 1369-1387. Retrieved from http://ajet.org.au

Rector, A. L. (1999). Clinical terminology: why is it so hard? *Methods of Information in Medicine, 38*(4/5), 239-252.

Reichelt, S., Häussler, R., Fütterer, G., Leister, N., Kato, H., Usukura, N., & Kanbayashi, Y. (2012). Full-range, complex spatial light modulator for real-time holography. *Optics letters, 37*(11), 1955-1957. doi:10.1364/OL.37.001955

Rico, R. D. T., Méndez, J. A. J., Mavar-Haramija, M., Perticone, M. A. R., & Prats-Galino, A. (2014). *Possibilities of application of 3D-PDF documents to represent models and tridimensional images in medicine.* Paper presented at the Proceedings of the Second International Conference on Technological Ecosystems for Enhancing Multiculturality.

Rogers, E. M., & Shoemaker, F. F. (1971). *Communication of Innovations; A Cross-Cultural Approach*. 866 Third Avenue, New York, N. Y. 10022 The Free Press.

Rolland, J., Davis, L., Hamza-Lup, F., Daly, J., Ha, Y., Martin, G., . . . Imielinska, C. (2003). Development of a training tool for endotracheal intubation: Distributed Augmented Reality. *Studies in health technology and informatics*, 288-294. doi:10.7916/D8CJ8C10

Rolland, J., Wright, D., & Kancherla, A. (1997). Towards a novel augmented-reality tool to visualize dynamic 3-D anatomy. *Studies in health technology and informatics*, 337-348. doi:10.3233/978-1-60750-883-0-337

Ruisoto, P., Juanes, J. A., Contador, I., Mayoral, P., & Prats-Galino, A. (2012). Experimental evidence for improved neuroimaging interpretation using three-dimensional graphic models. *Anatomical Sciences Education, 5*(3), 132-137. doi:10.1002/ase.1275

Ruisoto Palomera, P., Juanes Méndez, J. A., & Prats Galino, A. (2014). Enhancing neuroanatomy education using computer-based instructional material. *Computers in Human Behavior, 31*(0), 446-452. doi:10.1016/j.chb.2013.03.005

Ruthensteiner, B., Baeumler, N., & Barnes, D. G. (2010). Interactive 3D volume rendering in biomedical publications. *Micron, 41*(7), 886.e881-886.e817. doi:http://dx.doi.org/10.1016/j.micron.2010.03.010

Satava, R. M., & Jones, S. B. (1998). Current and future applications of virtual reality for medicine. *Proceedings of the Ieee, 86*(3), 484-489. doi:10.1109/5.662873

Schank, R. C., & Abelson, R. P. (2013). *Scripts, plans, goals, and understanding: An inquiry into human knowledge structures*: Psychology Press.

Schiemann, T., Freudenberg, J., Pflesser, B., Pommert, A., Priesmeyer, K., Riemer, M., . . . Höhne, K. H. (2000). Exploring the Visible Human using the VOXEL-MAN framework. *Computerized Medical Imaging and Graphics, 24*(3), 127-132. doi:10.1016/S0895-6111(00)00013-6

Selin, H., & Shapiro, H. (2003). *Medicine across cultures: history and practice of medicine in non-western cultures* (Vol. 3): Springer.

Sergovich, A., Johnson, M., & Wilson, T. D. (2010). Explorable three-dimensional digital model of the female pelvis, pelvic contents, and perineum for anatomical education. *Anatomical Sciences Education, 3*(3), 127-133. doi:10.1002/ase.135

Settapat, S., Achalakul, T., & Ohkura, M. (2014). Web-based 3D medical image visualization framework for biomedical engineering education. *Computer Applications in Engineering Education, 22*(2), 216-226. doi:10.1002/cae.20548

Sherman, W. R., & Craig, A. B. (2002). *Understanding virtual reality: Interface, application, and design*. San Francisco, CA: Elsevier.

Shin, D. S., Chung, M. S., Park, J. S., Park, H. S., Lee, S., Moon, Y. L., & Jang, H. G. (2012). Portable Document Format File Showing the Surface Models of Cadaver Whole Body. *J Korean Med Sci, 27*(8), 849-856.

Siddiquey, A. S., Husain, S. S., & Laila, S. Z. H. (2009). History of anatomy. *Bangladesh Journal of Anatomy, 7*(1), 1-3.

Simon, H. A. (1974). How big is a chunk. *Science, 183*(4124), 482-488.

Smalley, D. E., Nygaard, E., Squire, K., Van Wagoner, J., Rasmussen, J., Gneiting, S., . . . Peatross, J. (2018). A photophoretic-trap volumetric display. *Nature, 553*, 486. doi:10.1038/nature25176

https://www.nature.com/articles/nature25176#supplementary-information

Spitzer, V., Ackerman, M. J., Scherzinger, A. L., & Whitlock, D. (1996). The visible human male: a technical report. *Journal of the American Medical Informatics Association, 3*(2), 118-130. doi:10.1136/jamia.1996.96236280

Starreveld, Y. P., Gobbi, D. G., Finnis, K., & Peters, T. M. (2001). *Software components for medical image visualization and surgical planning*. Paper presented at the Medical Imaging 2001.

Straub, E. T. (2009). Understanding Technology Adoption: Theory and Future Directions for Informal Learning. *Review of Educational Research, 79*(2), 625-649. doi:10.3102/0034654308325896

Sulaiman, R. (2014). Visualization Cardiac Human Anatomy using Augmented Reality Mobile Application. *IJECCE, 5*(3), 497-501. Retrieved from

Sun, C., Chang, X., Cai, M., & Liu, J. (2014). An Improved Design of 3D Swept-Volume Volumetric Display. *Journal of Computers, 9*(1), 235-242.

Sweller, J. (1988). COGNITIVE LOAD DURING PROBLEM-SOLVING - EFFECTS ON LEARNING. *Cognitive Science, 12*(2), 257-285. doi:10.1207/s15516709cog1202_4

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction, 4*(4), 295-312. doi:10.1016/0959-4752(94)90003-5

Sweller, J., van Merrienboer, J. J. G., & Paas, F. (1998). Cognitive architecture and instructional design. *Educational Psychology Review, 10*(3), 251-296. doi:10.1023/a:1022193728205

Tan, S., Hu, A., Wilson, T., Ladak, H., Haase, P., & Fung, K. (2012). Role of a computer-generated three-dimensional laryngeal model in anatomy teaching for advanced learners. *The Journal of Laryngology & Otology, 126*(04), 395-401. doi:doi:10.1017/S0022215111002830

Teittinen, M. (2014). Depth Cues in the Human Visual System.

Teng, D. D., Pang, Z. Y., Liu, L. L., & Wang, B. A. (2014). Displaying three-dimensional medical objects by holographical technique. *Optical Engineering, 53*(11), 6. doi:10.1117/1.oe.53.11.112304

Thomas, K. J., Denham, B. E., & Dinolfo, J. D. (2011). Perceptions among occupational and physical therapy students of a nontraditional methodology for teaching laboratory gross anatomy. *Anatomical Sciences Education, 4*(2), 71-77. doi:10.1002/ase.208

Tong, J., Paulus, J., Eskofier, B., Schmidt, M., Lochmann, M., & Michelson, G. (2014). A correlation study between the novel Stereo Vision Perception test (StereoViPer test) and the Frisby test for measuring distance stereopsis. *Investigative Ophthalmology & Visual Science, 55*(13), 753-753.

Tourancheau, S., Sjöström, M., Olsson, R., Persson, A., Ericson, T., Rudling, J., & Norén, B. (2012). *Subjective evaluation of user experience in interactive 3D visualization in a medical context.* Paper presented at the Medical Imaging 2012: Image Perception, Observer Performance, and Technology Assessment.

Trelease, R. B. (1998). The virtual anatomy practical: A stereoscopic 3D interactive multimedia computer examination program. *Clinical Anatomy, 11*(2), 89-94. doi:10.1002/(SICI)1098-2353(1998)11:2<89::AID

Van Dam, A., & Feiner, S. K. (2014). *Computer graphics: principles and practice*: Pearson Education.

Van Mameren, H., Leiner, T., Wanders, A., & Van Der Vleuten, C. (1997). Anatomie/embryologieonderwijs aan de Universiteit Maastricht. Het oordeel van studenten geneeskunde. [Students' evaluation of anatomy/embryology teaching at Maastricht University.]. *Bull Med Onderwijs, 2*(91-100).

Van Merriënboer, J., Schuurman, J., De Croock, M., & Paas, F. (2002). Redirecting learners' attention during training: Effects on cognitive load, transfer test performance and training efficiency. *Learning and Instruction, 12*(1), 11-37.

Van Merriënboer, J. J., & Sweller, J. (2010). Cognitive load theory in health professional education: design principles and strategies. *Medical Education, 44*(1), 85-93.

van Merrienboer, J. J. G., & Sweller, J. (2005). Cognitive load theory and complex learning: Recent developments and future directions. *Educational Psychology Review, 17*(2), 147-177. doi:10.1007/s10648-005-3951-0

Vanderbilt. (2014). Course Descriptions: Nursing.

Venkatesh, V., & Davis, F. D. (2000). A theoretical extension of the technology acceptance model: Four longitudinal field studies. *Management science, 46*(2), 186-204.

Virk, Z. (2014). Golden Age of Islamic Medicine.

Visualization. (2015). *Merrian Webster Dictionary*.

Vorvick, L. (2012). Types of health care providers. *Medline Plus*.

Voyer, D., Voyer, S., & Bryden, M. P. (1995). Magnitude of sex differences in spatial abilities: a meta-analysis and consideration of critical variables. *Psychological bulletin, 117*(2), 250.

Wallach, H., & O'connell, D. (1953). The kinetic depth effect. *Journal of experimental psychology, 45*(4), 205.

Wanzel, K. R., Hamstra, S. J., Anastakis, D. J., Matsumoto, E. D., & Cusimano, M. D. (2002). Effect of visual-spatial ability on learning of spatially-complex surgical skills. *The Lancet, 359*(9302), 230-231. doi:http://dx.doi.org/10.1016/S0140-6736(02)07441-X

Wanzel, K. R., Hamstra, S. J., Caminiti, M. F., Anastakis, D. J., Grober, E. D., & Reznick, R. K. (2003). Visual-spatial ability correlates with efficiency of hand motion and successful surgical performance. *Surgery, 134*(5), 750-757.

Waterston, S. W., & Stewart, I. J. (2005). Survey of clinicians' attitudes to the anatomical teaching and knowledge of medical students. *Clin Anat, 18*(5), 380-384. doi:10.1002/ca.20101

Widmaier, E., Raff, H., & Strang, K. (2006). Cardiovascular physiology. *Vanders Human Physiology–The Mechanism of Body Function, 10th edn. McGraw-Hill*, 387-476.

Winkler, M. G. (1993). The Anatomical Theater. *Literature and medicine, 12*(1), 65-80.

Wong, W., & Tay, S. (2005). The teaching of Anatomy: the first hundred years (1905-2005). *Ann Acad Med Singapore, 34*, 72C-78C. doi:10.1.1.483.1757

Wu, H. K., & Shah, P. (2004). Exploring visuospatial thinking in chemistry learning. *Science Education, 88*(3), 465-492.

Xiao, X., Javidi, B., Martinez-Corral, M., & Stern, A. (2013). Advances in three-dimensional integral imaging: sensing, display, and applications [Invited]. *Applied optics, 52*(4), 546-560. doi:10.1364/AO.52.000546

Yammine, K. (2014). The Current Status of Anatomy Knowledge: Where Are We Now? Where Do We Need to Go and How Do We Get There? *Teaching and Learning in Medicine, 26*(2), 184-188. doi:10.1080/10401334.2014.883985

Yammine, K., & Violato, C. (2014). A meta-analysis of the educational effectiveness of three-dimensional visualization technologies in teaching anatomy. *Anatomical Sciences Education*. doi:10.1002/ase.1510

Yao, W. C., Regone, R. M., Huyhn, N., Butler, E. B., & Takashima, M. (2014). Three-dimensional sinus imaging as an adjunct to two-dimensional imaging to accelerate education and improve spatial orientation. *The Laryngoscope, 124*(3), 596-601. doi:10.1002/lary.24316

Yeom, S., Choi-Lundberg, D., Fluck, A., & Sale, A. (2013). *User Acceptance of a Haptic Interface for Learning Anatomy*. Paper presented at the International Conference on e-Learning.

Yeung, J. C., Fung, K., & Wilson, T. D. (2012). Prospective evaluation of a web-based three-dimensional cranial nerve simulation. *J Otolaryngol Head Neck Surg, 41*, 426-436. doi:10.2310/7070.2012.00049

Zariwny, A., Stewart, P., & Dryer, M. (2014). Visuo-haptic learning of the inner ear: using the optical glyphs and augmented reality of the InvisibleEar©™. *ACM SIGCAS Computers and Society, 44*(2), 5-7. doi:10.1145/2656870.2656871

Zhang, S. X., Heng, P. A., & Liu, Z. J. (2006). Chinese visible human project. *Clinical Anatomy, 19*(3), 204-215. doi:10.1002/ca.20273

Zhu, E., Hadadgar, A., Masiello, I., & Zary, N. (2014). Augmented reality in healthcare education: an integrative review. doi:10.7717/peerj.469

Zhu, H., Wang, W., Sun, J., Meng, Q., Yu, J., Qin, J., & Heng, P.-A. (2014). An Interactive Web-Based Navigation System for Learning Human Anatomy. *Advanced Technologies, Embedded and Multimedia for Human-centric Computing*, 73-81. doi:10.1007/978-94-007-7262-5_9

Ziegler, A., Mietchen, D., Faber, C., von Hausen, W., Schöbel, C., Sellerer, M., & Ziegler, A. (2011). Effectively incorporating selected multimedia content into medical publications. *BMC Medicine, 9*(1), 1-6. doi:10.1186/1741-7015-9-17