ABSTRACT

Title of Dissertation: INVESTIGATING THE DISRUPTIVE EFFECT OF COMPUTER GAME TECHNOLOGIES ON MEDICAL EDUCATION AND TRAINING

Roger D. Smith, Doctor of Management, 2008

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The computer gaming industry has begun to export powerful products and technologies from its initial entertainment roots to a number of "serious" industries. Game technologies are being adapted to defense, medicine, architecture, education, city planning, and government applications. Each of these industries is already served by an established group of companies that typically do not use computer games to serve their customers. The rapid growth in the power of game technologies and the growing social acceptance of these technologies has created an environment in which these are displacing other industry-specific computer hardware and software tools.

This dissertation proposes four hypotheses concerning the impact and acceptance of virtual reality and computer game technologies in education and training for laparoscopic surgery. It focuses on laparoscopic surgery because of the similarities between that form of surgery and virtual reality systems. The research indicates that the following four hypotheses are supported by the literature published in the field.

- Hypothesis 1: Training in laparoscopic surgery can be accomplished at a lower cost using virtual reality and game technology-based tools than through existing methods of training.
- Hypothesis 2: Virtual reality and game technology-based training environments provide better access to representative patient symptoms and allow more repetitive practice than existing forms of training.
- Hypothesis 3: Virtual reality and game technology-based training environments can reduce the training time required to achieve proficiency in laparoscopic procedures.
- Hypothesis 4: Virtual reality and game technology-based training can reduce the number of medical errors caused by residents and surgeons learning to perform laparoscopic procedures.

I also proposed a model of medical education in which virtual reality, including game technology, is the next major addition to or transformation of the medical education curriculum. The strong evidence collected in this study indicates that these systems are becoming much more accepted in medical education and that the technical limitations that existed when these devices were first introduced are already being overcome.

INVESTIGATING THE DISRUPTIVE EFFECT OF COMPUTER GAME TECHNOLOGIES ON MEDICAL EDUCATION AND TRAINING

By

Roger D. Smith.

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Dr. Michael Evanchik, Chair
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I am indebted to my mother and father for the foundations that they established in my early years and for always believing that I could accomplish great things. I only wish that my father had lived to see this newest accomplishment. Finally, my gratitude to my wife and children for allowing me to spend years shut in my office working toward this goal. Your understanding and support have been greatly appreciated.

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Chapter 1: Introduction and Research Problem

Medical education has traditionally been conducted on live patients, cadavers, live animals, collections of tissue and organs, and inanimate mannequins. The “gold standard” for perfecting operations has been the use of porcine subjects in place of humans. But for over 40 years researchers, surgeons, and scientists have been introducing computerized devices to augment or replace many of the traditional tools for training. The “Sim One” computerized mannequin is considered one of the first applications of computers to medical training. This system was conceived at an aerospace company in 1964, funded with a $272,000 grant from the Department of Education, and first demonstrated on March 17, 1967. Sim One delivered a mechanically animated, computer controlled mannequin that could receive and respond to two forms of gaseous anesthesia and four forms of injection. The “patient” breathed, had a heart beat, presented temporal and carotid pulse, and maintained blood pressure. The mannequin opened and closed its mouth, blinked its eyes, and changed these behaviors in response to anesthesia administered through a mask or a tube (Abrahamson, 1997). The device was enhanced in 1971 to deliver training in respirator application, endotrachael intubation, intramuscular injection, recovery room care, and the measurement of pulse and respiration (Hoffman & Abrahamson, 1975). Figure 1 shows the system in a classroom as it would be used for education.

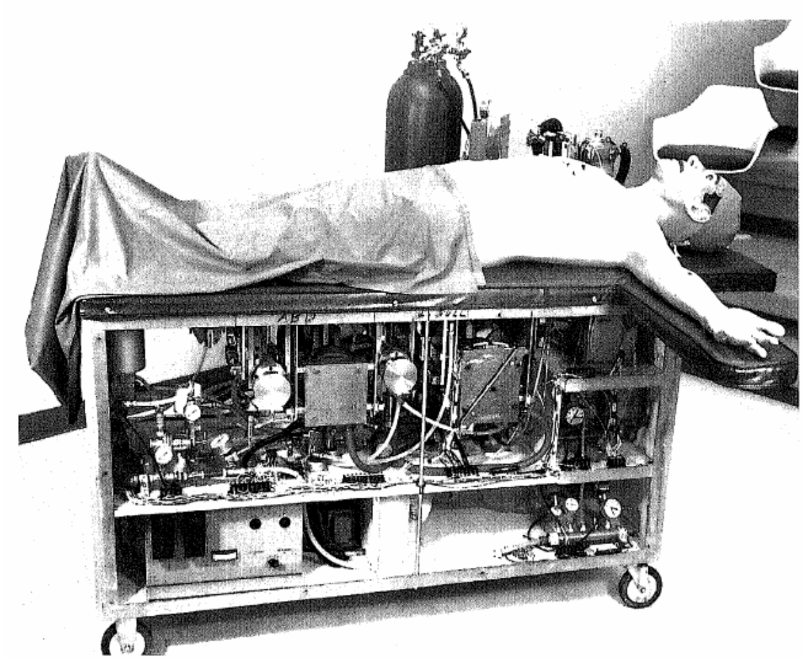

Figure 1. Sim One computerized training mannequin in 1967.

Source: Abrahamson, 1997

Hoffman and Abrahamson (1975) summarized the results of 15 different studies into the effectiveness of the device in improving performance in medical practice. These studies demonstrated improvements in “learning gain per unit of time, amount of student time required to reach criterion levels of performance, and investment of faculty time necessary for student learning.” The educational improvements that were achieved using what would today be considered primitive computers and animatronics were very impressive and suggest that further development of these devices could grow these advantages and add others that were not achievable forty years ago.

Virtual Reality

With Sim One and many later computerized mannequins as a foundation, new computer technologies have been introduced into medical training with the hope of carrying improvements deeper into the educational curriculum. One group of these technologies includes virtual reality and the software being created for modern computer games. The first medical virtual reality system based on a head mounted display and a data glove was introduced by Richard Satava and Jaron Lanier in 1991 (Satava, 1993). Lanier had coined the term "virtual reality" around 1984 to refer to the use of electronic devices for immersing humans into a computer generated world (the head mounted display) and to provide a tool with which to interact with that world (the data glove). Satava applied these to medical training and demonstrated how such a system might be employed to teach surgery. Satava's assessment of that system was that the technology was no where near good enough to be used in real training. He felt that it would take at least ten more years for the technology to reach a useful state (R. Satava, personal communication, January 10, 2008).

Early definitions of "virtual reality" required that a system must immerse at least one of the senses by cutting off access to the outside world and replacing it with a computer generated stimuli. However, a less strict definition often allows that the visual, audible, or tactile stimuli can be presented without totally eliminating external, non-computerized stimuli. This latter view has proven to be more practical and less expensive to develop and to sell to customers. In medical education, the term virtual reality is usually applied to any system where 3D computer images are being presented and manipulated. This categorization leads to computer games being referred to as virtual reality in most of the medical literature.

Computer Game Technologies

The computer gaming industry has begun to export powerful products and technologies from its initial entertainment roots to a number of "serious" industries. Game technologies are being adapted in defense, medical, architectural, educational, social, and governmental applications. Each of these industries is already served by an established group of companies that typically do not use computer games to serve their customers. The rapid growth in the power of game technologies and the growing social acceptance of these technologies has created an environment in which these are displacing other industry-specific computer hardware and software tools.

Computer games provide a rich environment in which to train a wide variety of tasks. The availability of the necessary computer hardware and game-based software technologies makes these an attractive alternative to existing methods of training (Lane, 1995; Mayo, 2007). This attraction is motivated by lower costs, higher effectiveness, and the increased accessibility of these systems. Halvorsen, Elle, & Fosse (2005) maintain that the lack of realistic computer graphics has been the primary obstacle to the adoption of simulators and VR devices by the medical profession. Therefore, I propose that computer games present root technologies which will have a disruptive effect on established providers in industries where these technologies can be applied (Christensen, 1997). In this dissertation I specifically investigate the impacts that these technologies can have in medical education and training. I propose a model of the power of game technologies that suggests increased future disruptions in medical education and training.

The dissertation will define what is meant by "game technologies"; identify similarities with previous technology disruptions; demonstrate the niche that these technologies are gaining in medical education; and present a model of medical education in which simulation, virtual reality, and game technologies contribute significant improvements to the educational process.

The power of games stem from several unique technologies that are embedded within them, their emotional connection to their customers, and the business ecosystems that they have created. Having evolved from their roots in Pong, Pac-man, Space Invaders, and Tetris, game makers have identified a combination of software technologies that are most effective at winning customers. Figure 2 illustrates these technologies with images. These dominant game technologies are: the 3D Engine, Accessible GUI, Physical Models, Artificial Intelligence, Networking , and Persistence

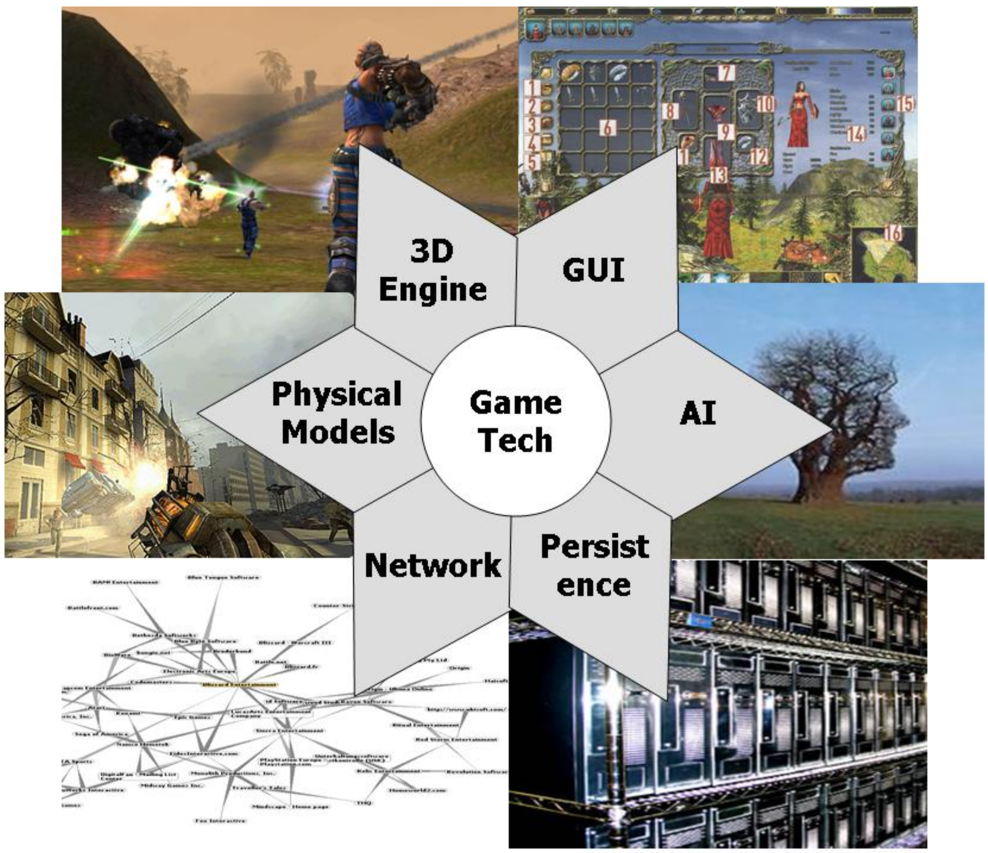

Figure 2. Six core game technologies that are potentially disruptive to other industries.

Source: Created by the author

3D Engine

Easily the most identifiable part of a game, the three-dimensional engine creates the graphics that a player stares at for hours. These engines are the key component with which vendors compete for market share. The detail of the characters, the vibrant colors, and realistic explosions all attract players and commercial users from one previously hot game title to the next.

Figure 3 provides a side-by-side comparison of a scene generated by *Wolfenstein 3D*, the first blockbuster 3D shooting game in 1992, with a comparable scene from the same company's *Quake 4* title in 2005.

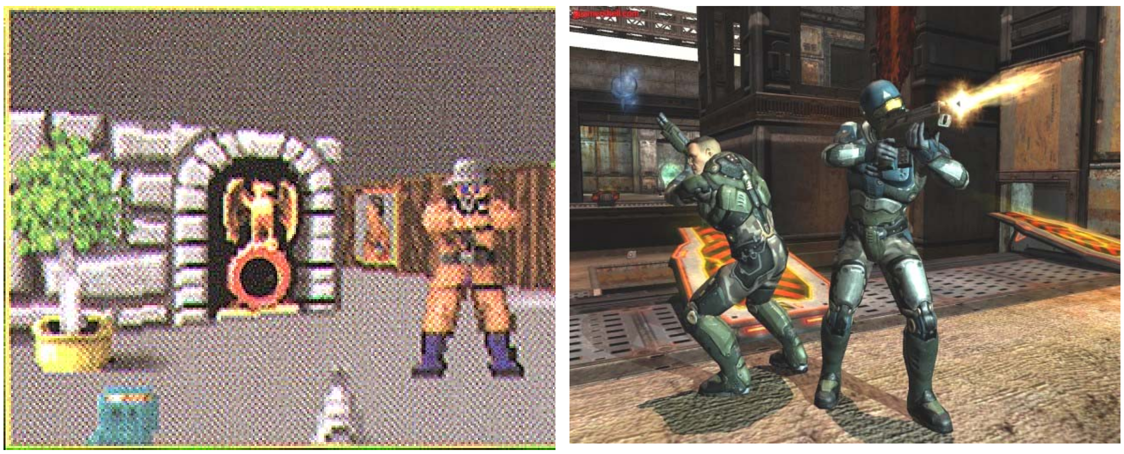

Figure 3. Visual comparison of 3D scenes from 1992 and 2005.

Source: id Software – http://www.idsoftware.com/.

The 3D engine is not just a game technology. There are a number of industries that require this type of capability to visualize information. Most prominently, these include flight simulator training, medical imaging, architecture, and computer aided design. Smed, Kaukoranta, & Hakonen (2002) illustrate the fact that the virtual environments created by a 3D engine are applied in different ways by different communities (Figure 4). Computer games, simulations, and virtual environments have significant overlap, but remain unique fields. This picture also illustrates the opportunities that exist for computer games and game technologies to infiltrate these very closely related industries. As I will demonstrate, the number of domains that intersect in this way far exceeds those considered by Smed.

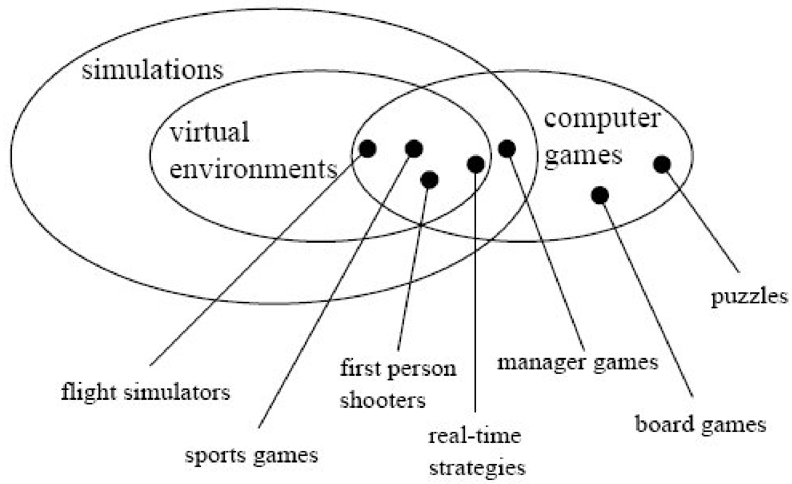

Figure 4. Unique domains of simulations, virtual environments, and computer games.

Source: Smed, Kaukoranta, & Hakonen, 2002

Graphical User Interface

"Why do we put up with the frustrations of everyday objects, with objects that we can't figure out how to use?" Rosen and Weil (1995) discovered that 25% of American adults had never used a personal computer, programmed a VCR, or selected the stations on their car radio. The authors lay the cause for this squarely at the feet of the complex user interfaces provided by the manufacturer. This is a popular problem for which a simple, non-threatening user interface would find a ready market.

In their attempts to attract and retain as large an audience as possible, computer game developers put significant effort into creating a graphical user interface (GUI) that is easily accessible and understandable. The ultimate goal is to make it possible for the largest audience to play the game without reading a manual. In fact, most games come with a familiarization stage in which the game teaches the player how the controls work and gives them simple tasks to perform to gain and demonstrate proficiency. This expertise in creating an effective human interface can be applied in hundreds of different industries to overcome the issues described by Rosen and Weil.

Physical Models

When playing a game, characters run, jump, shoot, fall, and explode. Each of these actions is controlled by physical models that estimate how real objects would perform these actions. As games have evolved, the first simple animations of running characters have been replaced with physics-based models that calculate how fast a specific vehicle can climb a hill and which objects would impede its progress. The accuracy of these models determines the realism of the world and the pictures that are drawn by the 3D engine.

The most recent advances in this area are the addition of “physics engines” which treat digital objects as if they had mass, weight, volume, stiffness, and joints that operate like real world objects. When movement and interactions occur, the physical properties of these objects interact with each other and with the gravity of the world to generate images that appear to be as real as the physical world we inhabit. Recently these physical models have been extended to include the movement and interactions of “soft” objects like vegetation, cloth, and human tissue. This is one of the necessary steps for entering the medical field.

Artificial Intelligence

A game in which only one player exists is very dull. The human player must encounter other characters that are interesting to interact with. These computer- generated characters must possess an artificial intelligence (AI) that allows them to perform all of the same actions that a human controlled character would, and to do so in a manner that appears realistic to the human player.

The AI techniques created in academic and industry labs have been adopted for games at a very rapid pace. In fact, leading AI researcher John Laird from the University of Michigan commented that the latest advances in AI appear in games long before they show up in more traditional industries (John Laird, personal communication, March 13, 2000). This makes the gaming industry an early adopter of academic research that will be embraced by other industries later.

Networking

The Internet connects live players with others around the globe. This means that each person is no longer limited to playing against an artificial opponent on his own computer, but can compete against anyone anywhere in the world. In fact, a player can locate others who have similar skill levels, those who have hours of experience with the game and will play in a unique and unpredictable manner. Novels like *The Most Dangerous Game* (Connell, 1924) have described the challenges of man-hunting-man in a fictional setting. These games have created a virtual world in which these novels are being brought to life.

Networking also enables the creation of a shared community with smaller groups, usually referred to as a “quest team”. These teams are very similar to the constructs needed to replicate an entire medical operation with all of the contributing medical specialists.

Those who enjoy the games are also eager to share their experiences through stories and advice within these communities. In a networked virtual world, there can be much more to the game than just the software in the box. It can open up an entire alternate social community in which people build relationships, create digital newspapers, and manage the business of the “clan.”

Persistence

Until 1997, most networked games created small vignettes in which a few players came together in a dungeon, castle, or fortress to team up and fight each other to the death – over and over and over again. But once the characters left the environment, all remnants of their engagement were deleted from the computer servers and the space was refreshed for the next team that would meet there. But, in 1997, the game *Ultima Online* changed all of that. The creators envisioned a world that was persistent through time. It existed before a player entered and after a player left. The actions that a player takes in the world persist there as they would in the real world. In this environment, the game becomes an evolving story that changes from one day to the next based on what all of the players do there. The success of *Ultima Online* led to a number of competitors like *Lineage, Everquest, Asheron's Call, The Sims Online,* and *World of Warcraft*. These game worlds can support hundreds of thousands of simultaneous players and evolve over many years. An alternate society in which a player can create a persistent identity is a powerful attractor for long-term players with long-term paying subscriptions.

These six core software technologies have pushed computer hardware manufacturers to create more powerful equipment. In fact, the game industry has become the primary force driving commercial computer advances – exceeding the demands of business productivity and military applications. The game community currently drives improvements in computational power, memory, graphics chips, display monitors, network connections, sound generation, user interface devices, and back-end server computers. Advances on all of these fronts benefit the other industries that use computers for their products and services, and most significantly, create a declining price/performance ratio that is enabled by the $18 to 19 billion annual game market (Jana, 2008; Leonard, 2008). It also builds an industrial computing environment that is capable of applying these game technologies when an application becomes available in a different industry, such as medical education.

Terminology Issues

Many non-entertainment industries find it difficult to use terms like “games” and “game technologies” when referring to the education and training that they take very seriously. This has been an issue within the military training community since just after World War II. At that time the military was both creating new and adopting existing paperboard war games for training leaders. However, these types of games had also become popular as a form of entertainment. Therefore, the military kept the serious use of these a secret for fear of public ridicule of their methods (Ghamari-Tabrizi, 1995).

Similarly, the medical profession deals with life threatening situations and it is currently seen as inappropriate to use “games” to train for these situations. Therefore, in the literature there is almost never any reference to a “computer game” for medical education and training. Instead such systems are referred to as “virtual reality”, keeping them under the umbrella of the academic research work that was initiated in the late 1990’s. Some authors use the term “microsimulations”, classifying them as smaller versions of the large computer-driven mannequin devices that are widely accepted (Binstadt et al, 2007). In this dissertation I will generally refer to the technologies as “virtual reality” (VR) in order to be consistent with the published literature and to maintain the distinction between systems for entertainment and those for medical training. The term “simulation” in this dissertation will refer to hardware, software, and tactile devices that attempt to replicate the real world, typically in the form of a human mannequin. In the medical field simulation and VR are often combined into a single training device.

Surgical Practice and Education

Ziv, Wolpe, Small & Glick (2003) point out that simulation and virtual reality have been used for training in other "high-hazard professions" for decades. They list the nuclear power, aviation, and military training industries as leaders in the practice. Health care has lagged behind in adopting new technologies that are effective forms of training because of the costs involved, the lack of rigorous proof of effectiveness, and dogged resistance to change. But this resistance has been waning over the last decade as simulation and virtual reality have made rapid improvements. Surgery itself is changing. Minimally invasive surgical techniques, such as laparoscopy, endoscopy, and arthroscopy, have proven so medically beneficial and popular with patients that they are being applied to as many operations as possible. Patients experience significantly less physical trauma and recover much faster from laparoscopic than from traditional open surgical procedures. These benefits translate directly into reduced costs for medical care.

The surgical interface used during laparoscopic surgery is most amenable to the application of virtual reality and simulation. The close bond between the surgeon and the patient is already intermediated by the use of a computer monitor for viewing the images from a small camera inserted into the patient's body. Laparoscopic instruments also remove the surgeon's hands from direct contact with the human body. These two user interface devices have similarities to virtual reality interfaces and make the entire procedure much more replicable in a virtual environment.

Researchers and surgeons emphasize the confluence of a number of factors that call for changes in the way surgeons are trained. One author has called the current situation a "perfect storm" that demands a reassessment of traditional education practices (Murphy, Torsher, & Dunn, 2007). Specifically the literature shows concerns in the following areas.

- *Risk.* Practicing on patients poses a risk to the patient's health. Practicing on animals poses a risk to the medical student (e.g. cases of the transference of mad cow disease have been reported). (McDougall, 2007)
- *Cost.* The cost of equipment, facilities, animals, and cadavers present barriers to extensive training. (Bridges & Diamond, 1999)
- *Availability*. Training opportunities have been reduced because patients are spending less time in the hospital, residents have restrictions on the number of hours they can work, and medical schools are experiencing reduced funding. (Birden & Page, 2007; Davis, Thompson, & O'Brien, 1999)
- *Access*. Students cannot access educational opportunities on their own initiative. In most cases, the education has to be organized, scheduled, and delivered by the organization. (Dunkin, Adrales, Apelgren, & Mellinger, 2007; Halvorsen et al, 2005; Spitzer, 1997)
- *Limited Hours*. Residents are limited to a maximum of 80 hours per week in the hospital. This is a significant reduction from previous practice and is reducing the opportunity for each resident to experience a breadth of symptoms presented by live patients. (Satava, 2004b)
- *Ethics*. It is becoming unacceptable to practice procedures on anesthetized patients and animals. This ethical restriction is currently stronger in Europe and Australia than in the US. (Satava, 2004a; Murphy et al, 2007)

- *Expectations*. New students come from a generation that is infused with computers and electronic devices. They expect to use computers and simulations to learn. (Murphy et al, 2007)
- *Insurance*. There is increasing pressure to lower all costs, including those that are tied to medical education. Financial restrictions from these third parties are limiting older forms of education. (e.g. When a medical student performs a necessary intubation on a patient, this is a training event, but it is also a billable procedure. Insurance companies are trying to stop this.) (Satava, 2004a)
- *Volume*. Modern technologies have created a much larger number of procedures that surgeons are expected to master. The education system is challenged to teach more information in the same or less time. (Reznick & MacRae, 2006)
- *Complexity*. Modern technologies allow a surgeon to perform procedures that are much more complex than those of a previous generation. The existing methods of educating students are not effective at building expertise in these procedures. (e.g. Laparoscopic surgery cannot be learned through observation.) (McDougall, 2007)
- *Quality of Technology*. Simulation and VR are becoming much more realistic than when they were first introduced in the 1960s. The fidelity of these devices is high enough to present training that is equal to or better than traditional methods. (Murphy et al, 2007)
- *Professional Acceptance*. Medical educators see that simulators and VR are being used for training in commercial aviation, military operations, and nuclear power. These professions risk human life, putting them in the same category as surgeons, which adds credence to the acceptance of simulators and VR for medical education. (Ziv et al, 2003)

- *Learning from Mistakes*. Working with live patients and animals makes it difficult or impossible to intentionally present the resident with a surgical mistake that must be corrected. (Ziv, Ben-Davis, & Ziv 2005)
- *Proficiency-based Medicine*. Graduation and certification demand demonstrated psychomotor skills, as opposed to the previous knowledge-based standards. Simulation and virtual reality are a means of developing these skills. (Murray, 2005)

Surgical practice is changing in a manner that makes it more amenable to the use of simulation, virtual reality, and computer game technologies. Open surgery is being replaced by minimally invasive procedures and traditional surgical tools are being supplemented with laparoscopic and robotic tools. Virtual reality and computer game technologies are able to create visually and physically accurate representations of these types of operations. The VR interfaces are very similar to those used in laparoscopic and robotic surgery.

Robotic surgery takes this separation even further. Devices like the Da Vinci surgical robot allow the surgeon to sit at a computer controlled operating station that is many feet or even many miles removed from the patient. The effectors of the robot are directly working on the patient while a camera delivers video to the doctor and computer networks deliver instrument controls to the patient-side robot.

Researchers are further transforming surgery by creating miniature effectors that are small enough to be inserted entirely into the human body and can be controlled remotely through radio transmissions and/or magnetic fields. In these cases, there may be very little or no need to open the patient for surgery. These 21st century surgical methods are very different from traditional open surgeries. In addition to being more amenable to virtual reality for training, they also create new challenges in mastering surgical skills (Dankelman & Di Lorenzo, 2005; Birden & Page, 2007). These challenges often cannot be addressed through traditional apprenticeship learning models that rely on practice with living patients (Shalhav, Dabagia, Wagner, Koch, & Lingman, 2002). The changes that have already occurred demand a new perspective on education that explores tools and techniques from other professions.

Research Problem

The primary assertion of this dissertation is that computer game technologies, often referred to as virtual reality, offers a valuable training alternative to established technologies in non-entertainment industries, and that in the medical industry they can make valuable contributions toward training surgeons, specialists, general practitioners, medical students, nurses, and medical technicians. The compelling advantages that would drive the adoption of game technologies in this field, as with many other fields are reduced costs, increased access to training scenarios, reduced training time, and reduced errors in execution.

If these technologies are to make significant inroads into the training of medical practitioners, then they must present at least one and preferably multiple advantages over existing methods of training. The literature review exposes numerous advantages that have accrued to medical training through the adoption of simulators for training. Medical education has traditionally been focused on the mastery of knowledge and the investment of sufficient hours in a classroom. Graduation or certification is not generally based on proficiency in psychomotor skills. In fact, such proficiency is seldom even measured (Satava, 2005a). Computer-based simulations offer an opportunity to measure performance on every task and to push practitioners toward a level of proficiency rather than a mastery of knowledge. The rapid growth of the number of medical procedures, pharmaceuticals, diagnostic tests, equipment, and surgical tools has created an environment in which surgeons do not have sufficient time to be trained in all of them under the current system using the current educational methods. Finally, patients presenting the necessary conditions to serve as teaching cases are not available in sufficient numbers to adequately train all skills in a live patient-based environment. Simulations and virtual reality have been shown to offer improvements in all of these situations.

Improvements have also been observed in moving from simulators to game-based systems in non-medical industries (Lane, 1995; Mayo, 2007). One of the primary concerns surrounding simulators like the Human Patient Simulator (HPS) has been the cost of the device. Ranging from $100,000 to $500,000 each, even well-funded facilities can afford only a few these, while smaller facilities have been unable to purchase even a single simulator (Issenberg et al, 2005). Game-based systems use consumer grade computers and can be deployed to multiple classrooms, hospitals, and individual students at much lower prices. The ability to put these trainers in more hands allows the student to practice more frequently on their own schedule, significantly contributing to their proficiency. There are also claims that the mental and emotional engagements that are fostered by games leads to a better understanding of the material by students and an increased willingness to repeat scenarios until they are successful (Steinkuehler, 2007).

Simulations are often seen as competitors for training time and funding that could be applied to physical mock-ups with mannequins, cadavers, and animals. The use of classroom instruction versus physical mock-ups is a question that has been settled for many centuries and the two have reached an acceptable, though not necessarily substantiated, balance in various educational curriculums. The addition of simulations and virtual reality into this environment is disruptive and requires that these new techniques prove their value in the training mix.

Operating on human or animal cadavers is one form of training using physical mock-ups. However, this type of realism can significantly increase costs, which in turn can have a negative impact on access to that form of training. Therefore, its strengths are achieved through higher costs, which places limitations on access to the training and negatively impacts the level of proficiency derived from training with cadavers.

Computer-based tools (e.g. simulators, virtual reality, and games) also impact the cost of, access to, and effectiveness of training. These tools allow a reduction in cadaver and animal-based methods and, as a result, lower the cost of training. Lower costs can then increase assess to the tools because they can be purchased and distributed in larger number and can be used more frequently. These new methods also support automated data collection and analysis. This data enables objective feedback which can positively contribute to the effectiveness of this form of training.

The primary advantages of early simulators and the virtual reality systems that are following in their wake are cost, accessibility, time investment, and error reduction (Michael & Chen, 2005; Bergeron, 2006). Simulators and games provide systems that are significantly lower in cost than many of the alternatives used in a physical mock-up environment. For example, one of the preferred methods of teaching internal anatomy and procedures for working inside the human body is to present the students with human cadavers or anesthetized animals. It is expensive to acquire these bodies, store them, and dispose of them when finished. It is also expensive to provide the operating environment in which the students must work.

Most industries, including the medical profession, maintain that effective training must be conducted in a realistic environment, preferably through an apprenticeship during real activities. However, there is a significant body of knowledge that must be mastered before apprenticeships can be effective. Simulators and virtual reality systems offer the opportunity to teach the information, procedures, and relationships that make up this body of knowledge and to do so in a measurably effective manner. When learning about internal anatomy, anesthetized animals are lower cost and more accessible than human cadavers. But their internal anatomy can be significantly different from that of a human, making this training less effective than working with human cadavers.

Like many other industries, in medical education, access to the tools and situations necessary for training can be very difficult. Given limited resources and busy schedules, live training procedures can be conducted only rarely, significantly limiting the training opportunities of residents. Even simulators can be expensive devices that have to be prepared by experts and are not generally approachable by a student without technical assistance (Nehring, Ellis, & Lashley, 2001). Game-based training can be encapsulated in a personal computer and accessed by the trainee according to his/her schedule. This means that the student can train much more often than through most other methods.

Chapter 2: Literature Review

Medical Education with Virtual Reality

There is a rich literature on the use of simulation and virtual reality in medical education. It appears to begin with Hoffman's 1975 paper describing the "Sim One" device and proceeds to the current day with a constant stream of experiments into the effectiveness of using a wide variety of modern computer and visualization devices in numerous medical specialties. In the 1970's the primary focus of simulation was on training in anesthesiology, that being the most approachable with the technology that was available. In the 1990's the rapid growth of minimally invasive, endoscopic, laparoscopic, and arthroscopic surgeries led to the need for improved methods of teaching those skills. This resulted in the significant use of simulators and virtual reality for this purpose. Finally, the primacy of cardiac trauma and the emergence of full-body mannequins equipped with computerized controls led to an entire industry and family of devices dedicated to these applications (Issenberg et al, 1999). Once created these computerized mannequins offer multiple applications in improving care to the patient (Nehring et al, 2001). Issenberg was particularly interested in the potential for these systems to support life-long learning by surgeons.

Poss et al (2000) point out that arthroscopy of the knee is an ideal environment for a simulation because the surgeon is already operating in a quasi-virtual environment. Images of the operation are provided via a computer monitor rather than being directly viewed as in open surgery. The end effectors of the operating instruments are also not directly visible by the surgeon, but must be followed on the computer monitor.

Riley, Wilkes, & Freeman (1997) surveyed 183 anesthetists to determine where these simulators could best be used in their profession. Most felt that they belonged in the educational curriculum, but that they should not be used to determine certification in a specialty.

Schwind (2001) describes training in Advanced Cardiac Life-Support (ACLS) and their discovery that physicians retain the guidelines for these procedures much better if they are trained with a simulator than if they merely review a textbook. They describe the ACLS Simulator which is designed to take physicians through the processes using an interactive, computer-based simulation with a graphical user interface. The interface uses primitive forms of computer game displays and could be significantly improved with current technology. The simulator also incorporates video of real doctors treating mannequins. This may present an opportunity to incorporate 3D game engine displays that are much more flexible in responding to the actions of the student.

Pioneers in Medical Simulation

In 1964 Tullio Ronzoni with defense contractor AeroSpace General, Stephen Hoffman with the University of Southern California Medical School, and J. Samuel Denson with the Los Angeles County General Hospital created a partnership to explore the use of military simulation technologies in medical education. Hoffman suggested a system that would present all of the dials and meters that an anesthesiologist monitors for a patient under surgery. Later, a team of engineers at AeroSpace General suggested adding a whole body mannequin to make the system more realistic (Figure 5). This team created Sim One and opened the doors for the use of simulators and technologies from the defense industry to enter the medical education profession. This crossover of ideas was waiting on sufficient maturity and capability in the technologies to make the transition possible and valuable. By 1967, Sim One was finished and demonstrated at

Columbia University. The effectiveness of the device was tested on a class of twelve anesthesiology residents at the Los Angeles County General Hospital (Abrahamson, Denson, & Wolf, 1969; Denson & Abrahamson, 1969; Hoffman & Abrahamson, 1975).

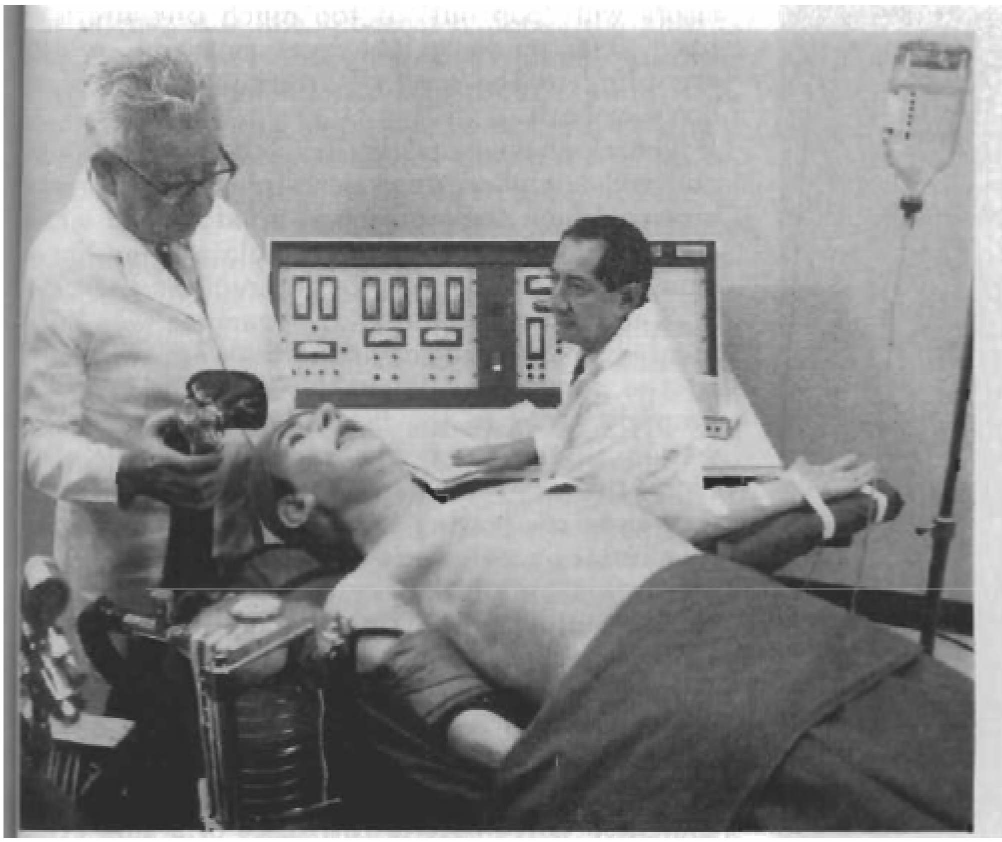

Figure 5. Denson (left) and Hoffman (right) demonstrate Sim One in 1967.

Source: Denson & Abrahamson, 1969

From the beginning, issues such as the cost of the device, its ability to replace or supplement other forms of training, and the potential to reduce medical errors were central to its value to the medical community. The pattern of recognizing the potential of technology from other domains, finding a proponent to support the creation of a prototype, demonstrating the system to an audience of peers, and scientific experimentation into its effectiveness was set. This same pattern has been used for hundreds of simulators and virtual reality systems since Ronzoni, Hoffman, and Denson created this first device. Hoffman's account of the early process makes little reference to resistance to the device by anesthesiologists or the educational community.

Simulation as a Tool for Education

Given the current prevalence of a wide variety of simulation devices in medical education, a number of authors have attempted to create categories to aid in discussions and applications of the devices. Binstadt et al (2007) suggest the following:

- *Mannequin-based* refers to the use a computer-controlled, full-size adult replica,
- *Microsimulation* uses a PC and Internet connection to provide a small environment for interacting with a virtual patient,
- *Partial-task* systems use a partial body mannequin that represents a specific body system or function,
- *Dedicated Task* systems focus on a single procedure, and
- *Virtual Reality* which incorporates tactile feedback devices.

Notice that he makes a distinction between virtual reality and microsimulation, insisting that tactile feedback is the key feature of VR systems. This view is not shared by all authors. He also points out that all of these systems have declined significantly in cost, often by a factor of five, and provides evidence of cases in which surgical performance has been significantly improved through their use.

Richard Satava (2004a) was one of the first to experiment with VR in medical education and he refers to 3D visualization using a PC as a form of virtual reality. He also argues that a surgeon requires both cognitive skills and technical skills. The latter are best created through hands-on experience and practice, the kinds of activities that are accomplished with a simulator and in virtual reality. These information technologies may disrupt the current medical education process because they allow both learner-directed education and performance-based assessment, which could lead to some students moving through the curriculum at a more rapid pace than others, and graduating sooner. Garden, Robinson, Weller, Wilson, & Crone (2002) support this perspective as well, and add that purely didactic learning is inferior to practical hands-on experiences that are provided with simulators and virtual reality.

Advances in surgical technologies and techniques have created a profession in which there are many more procedures for s surgeon to master than were required of previous generations. McDougall (2007) maintains that the complexity of modern surgery has already exceeded the ability of the traditional apprenticeship model of education to provide all of the knowledge and experience necessary to create a qualified surgeon. This perspective is supported by Aggarwal et al (2007), who feels that the time has come to allow simulators and virtual reality systems to be used to insure that all residents are exposed to every set of symptoms necessary for their fundamental education. He argues that it is no longer acceptable to rely on the chance circumstances surrounding a teaching hospital to deliver these experiences while a resident is present. He believes that a simulator can empower the transition from a knowledge-based to a proficiency-based system of education, graduation, and certification.

Murphy et al (2007) provides a list of 18 advantages of using simulation rather than traditional methods in teaching intensive care techniques. Most of these focus on the ability to improve the performance of the surgeon and to measure that performance prior to graduation. Ziv et al (2005) adds that the traditional medical curriculum only familiarizes the resident with successful procedures and outcomes. Limited resources and the ethical constraints of working with live patients make it impossible to familiarize the resident with mistakes and failures. This is something that virtual reality can deliver that is unique from the existing methods of education.

Issenberg (2005) conducted a survey of five literature databases to determine “What are the features and uses of high-fidelity medical simulations that lead to the most effective learning?” This study identified the following useful features of medical simulation:

- Provides educational feedback,
- Allows repetitive practice,
- Can be integrated with the curriculum,
- Presents ranges of difficulty levels,
- Supports multiple learning strategies,
- Captures clinical variations,
- Provides a controlled environment,
- Enables individualized learning,
- Captures defined outcomes, and
- Allows for validation of training method.

Chui et al (2006) have created a training system that uses both simulation and game technologies to teach surgeons to perform a specific type of surgery. The system includes a tactile/haptic device which accurately represents the force feedback that surgeons feel when inserting a needle through different body materials. The authors consider the mathematic models that represent the human body and the instructions that are given to the haptic device to be simulation. They consider the 3D visual displays to be computer game technologies. They believe that both of these technologies are important parts of the training system.

Byrne & Greaves (2001) agree with Riley et al (1997) that it would be premature to use simulators to certify specialties. They also accept low, intermediate, and high fidelity classes of simulations – in which computer games and virtual reality would be classified as high fidelity.

Cost Factors in Medical Education

Medical training has been conducted in a number of different modes prior to the introduction of computers, simulators, and virtual reality. These include textbook readings, lectures, operations on human and animal body parts, full human cadavers, full animal cadavers, and apprenticeships in hospitals. Each of these offers advantages in effectiveness, cost, and accessibility. As new simulators and virtual reality systems are added to the mixture, these will have to demonstrate their value just as the previous methods have done.

Bridges & Diamond (1999) maintain that surgical residents cannot effectively be trained in the operating room because of the extremely high costs required to use this method. They provides data from 14,452 cases of 46 different procedures in which the cost of performing an operation was significantly higher when teaching a resident. They estimate that this cost is $47,970 per graduating resident. This accrues to a cost of $53 million per year across the medical education field. However, their calculations assume that one hour of operating room time costs only $257. Other authors have estimated this cost at between $1,000 and $1,500 per hour (Frost & Sullivan, 2004; Hyltander, 2003.) In specific areas like laparoscopic surgery, researchers have found that they can significantly reduce training costs by using virtual reality devices in place of animals and box trainers (Brunner et al, 2005; Eastridge et al, 2003).

Since the time associated with using assets like operating rooms and professional staff translate directly to costs, any reduction in the duration of use of these assets results in a measurable cost saving. Virtual reality systems are one cost effective means of achieving these savings (Korndorffer, Stefanidis, & Scott, 2006; Madan et al, 2003). McClusky et al (2005) points out that VR eliminates the repetitive material costs associated with biological surrogates like tissue samples, organs, animals, and cadavers. McNatt & Smith (2001) believe that these substitutions are especially important in the early stages of a resident's education when the student is least likely to appreciate the subtle information that comes from working with real tissue.

Rosser et al (2007) reports on a national study which found that all medical errors carry a cost of $37.6 billion per year in the United States. Moving resident practice out of the operating room and into virtual reality is one means of significantly reducing these errors and their associated costs. Pearson, Gallaher, Rosser, & Satava (2002) believe that these factors are so relevant that they will drive continuing medical education and certification courses to be conducted primarily in VR by 2010.

Kurrek & Devitt (1997) describe the design and the costs for creating an anesthesia simulation environment. Their team created a mock operating theater with computer-driven patients and a VR projection environment for $665,000. The system requires a major up front investment, but once established, it can be used to train thousands of residents at a much lower cost than bringing them into a real operating room.

Teaching hospitals are under pressure to increase their financial productivity, which means performing more surgeries and doing them more quickly (Dunkin et al, 2007.) Such an environment is not conducive to teaching a resident. Absent time with faculty members, Dunkin et al recommend creating simulation laboratories in which residents can train themselves during their own free time – primarily during the middle of the night when they are on call. They believe this will be an important part of a new self-directed learning trend in education.

Access to Patient Symptoms and Virtual Reality

Ritter & Bowyer (2005) describe the success of the TraumaMan mannequin in providing a device that can be used to teach “cricothyroidotomy, chest tube insertion, pericardiocentesis, diagnostic peritoneal lavage, and cut down for venous access.” The device has been adopted by half of all advanced trauma life support courses in place of animals and cadavers. This makes it possible to teach these skills at facilities that do not have animal lab facilities. Good (2003) points out that the Human Patient Simulator (HPS) is used by one third of medical schools and universities around the world. These allow the presentation of rare and complex clinical problems. Waseda, Inaki, Mailaender, & Buess (2005) describe the importance of alternate training devices in Europe due to the restrictions on using live animals in those countries. This has led to the creation of several box trainers that contain animal parts, but do not require operating on a living animal.

In many states there are legal restrictions on the number of hours that a student resident can spend in the hospital each week, usually 80 hours maximum. Residents had previously spent many more hours working due to demands from the institution and their own desire to experience as many cases as possible. The legal restrictions are meant to protect patients and residents from mistakes due to fatigue. But they are also significantly reducing the amount of experience that a resident has upon graduation (Brunner et al, 2005). Brunner et al suggest that virtual reality and simulation systems are a means through which some of this experience can be restored. Other authors have suggested that virtual reality systems are ideal ways for a resident to spend many unoccupied hours during graveyard shifts (Dunkin et al, 2007). Madan's experiments revealed that students found VR stimulating and interesting enough to keep their attention, a characteristic that may be imperative to motivate self-study during these free hours (Madan, Frantzides, Tebbit, & Quiros 2005b). One possible circumvention of the 80 hour work week limitation would be the use of a VR system by students at home. McClusky et al (2005) describe the ProSim-J laparoscopic surgery trainer which is based on a laptop computer and a few special effectors. It is compact and affordable enough to allow students to purchase one and use it anywhere they like.

Though most residents and faculty members would prefer that the resident learn from live cases in the hospital, emergency room, and operating theater, it is clear that each of these experiences is unique. The knowledge assimilated by a resident during one exposure is not necessarily replicable in another; neither can it be measured to determine exactly what was learned and retained. One significant advantage of simulators, including VR systems, is that they can be programmed to deliver a very specific set of knowledge repeatedly. They can also measure the resident's proficiency in judgment and psychomotor skills, something that is very difficult in live cases (Grantcharov, Bardram, Funch-Jensen, & Rosenberg, 2003b; Maithel et al, 2006). Grantcharov et al (2003b) demonstrated this specifically for the MIST-VR laparoscopic surgery trainer.

Issues with accessing specific sets of symptoms are not new and have been addressed with animals, mannequins, and box trainers in the past. But researchers have been comparing the effects of VR systems to those older methods. Jordan, Gallaher, McGuigan, & McClure (2001) found that the MIST-VR system was more effective at teaching specific skills than the older box trainer devices. Schijven, Jakimowicz, Broeders, & Tseng (2005b) found MIST-VR to be better than learning by lecture, videotape, or observation of real laparoscopic surgeries. Madan & Frantzides (2007) countered these studies with his own which showed that VR trainers were equivalent to box trainers.

A specific skill cannot be mastered by a single practice on one patient or by observing the procedure on multiple patients. Grantcharov et al (2003a) maintain that a surgeon must practice a procedure between ten and thirty times to become truly proficient at it. Such a large number of repetitions are only approachable with a training device. Only computer-driven devices are flexible enough to be modified to allow multiple techniques and scenarios to be practiced.

Established practicing physicians are currently learning laparoscopic surgery through weekend seminars where they have little access to real patients with real symptoms. This environment requires the use of either animal models or simulators to provide the practice that is necessary to master the skills (Korndorffer et al, 2006). Kothari, Kaplan, DeMaria, Broderick, & Merrell (2002) have found that VR systems are equivalent to a 5-day skills course which use animal models and organ boxes. Aggarwal & Darzi (2006) insist that a surgeon must master laparoscopic skills prior to entering the operating room, not while they are in the operating room. Historically many surgeons have “practiced” on patients and this method is not acceptable in the current medical environment.

DeMaria, McBride, Broderick, & Kaplan (2005) demonstrated a need for an alternative method to measure effectiveness of laparoscopic surgery. They were investigating the impacts of fatigue on performance, specifically for on-call residents in the middle of the night. It would have been inappropriate to intentionally encourage fatigued residents to conduct surgeries on patients to support this study. It would also have been impractical or impossible to get the necessary number of patients for the study. They used the MIST-VR system as a surrogate for real surgery. It was able to measure variations in performance of fatigued residents without threatening the health of a real patient or requiring the consumption of multiple animal or organ models.

Simulation and VR Impact on Training Time

Research into the impact of VR and simulators on learning time has led to a number of discoveries in this area. First, simulators are generally able to convey skills to a student faster than traditional methods (Grantcharov et al, 2003b). Second, students who learn their skills using these devices are being shown to perform real surgeries more quickly than their traditionally trained counterparts. The primary speculation on this is that they are more confident in their skills and proceed more quickly and with less hesitation and time to assess the situation. Third, the rapid growth in medical knowledge is challenging the established system of education to deliver everything that a student must know and be able to do in the short time available (Jordan et al, 2000). As a result, medical educators and researchers are eager to find new methods of training that can help with this problem. Laparoscopic surgery is one of the new skills that are in great demand by the patients and hospitals, but which has not generally been part of the academic curriculum (Shalhav et al, 2002).

Birden & Page (2007) argues that the amount of knowledge required in modern medical education has increased substantially and that there is relatively little time to present all of it to a resident. They encourage the use of learning teams and evidence-based practice as effective means of teaching the material. Evidence is difficult to collect in traditional learning environments, but its collection is a natural feature of computer-based training systems. The automated collection of performance data can enable the use of proficiency-based curriculum in which students progress at a rate determined by their individual proficiency, rather than at a uniform rate set for the slowest students.

Dankelman, Chmarra, Verdaasdonk, Stassen, & Grimbergen (2005) feel strongly that residents must not learn their skills on live patients. Given the evidence that it requires between 10 and 30 repetitions of a procedure to achieve proficiency (Grancharov et al, 2003a; Stefanidis et al, 2006b); they advocate that these first ten to thirty repetitions occur on a simulator, mannequin, organ box trainer, or virtual reality device. They also suggest that virtual reality and simulators can be used to improve the selection process for admitting students to a program. Finally, they believe that these training devices can be used to rehearse specific procedures and significantly reduce the stress that new residents feel when faced with a live patient operation. Adamsen et al (2005) also found that VR systems can identify which residents and surgeons are experienced in specific procedures. This was a necessary step in determining whether the devices could be used as tools to certify surgeons or to determine when specific educational programs can be ended.

Virtual reality systems like AccuTouch, also marketed at Laparoscopy VR, from Immersion Medical has been the subject of a study by Frost & Sullivan to determine the Return on Investment for these devices. Their interviews with health providers indicated that students learned laparoscopic skills more quickly with a simulator than through observation and practice with animals (Frost & Sullivan, 2004).

Madan et al (2003) has found that game-playing skills are positively correlated with laparoscopic skills, providing support to studies which are attempting to show that the skills learned in laparoscopic-specific training devices are transferable to real surgery. Brunner et al (2004) has shown that the MIST-VR system can lead to measurable proficiency improvements.

The rapid growth in popularity and demand for laparoscopic methods in every procedure possible led to an immediate shortage of surgeons who were qualified to do the surgeries. Short multi-day seminar courses were created to teach these skills and to develop a level of proficiency that would be acceptable in hospitals. These seminars were faced with issues around acquiring sufficient practice materials, such as animal models, tissue, and organs, to allow the students to practice. VR simulators have become one of the alternatives to these materials and they allow a seminar to include more students due to the degree of automation in classroom preparation and in measuring student performance (Shalhav et al, 2002). Seymour's finding (2002) that VR leads to faster skill development also implies that seminars using VR can be shorter than those using animal tissue.

Potential to Reduce Medical Errors

Across the medical profession, medical errors result in between 44,000 and 98,000 deaths each year (Cohen, Corrigan, & Donaldson, 1999). These statistics have become the focus of a Blue Ribbon study groups to identify the causes and to mitigate them. One area of focus has been medical education and the process used to determine when residents and surgeons are qualified in specific procedures. In one study, researchers estimated that in anesthesiology, like aviation, 65-70% of incidents and accidents are the result of human error (Howard, Gaba, Fish, Yang, & Sarnquist, 1992.) Also, real crises are rare events that most practitioners have no hands-on experience with and can only be exposed to in a simulator. Howard et al believe that this type of familiarization and rehearsal is a critical role for a simulator. Also, over the last ten years it has become evident that the sudden popularity of laparoscopic surgery has led to increases in the number of errors due to a lack of experience and education (Huang, Payandeh, Doris, & Hajshirmohammadi, 2005). Though this is to be expected with a new procedure, researchers have noticed that the error rates are not decreasing over time and remain approximately three times higher than for more traditional open surgical procedures.

Numerous researchers and educators are exploring the use of virtual reality and simulators as a means of improving the medical education system. They are looking to these tools, not as equivalent experiences to traditional education, but as improvements over these methods. Wayne et al (2005) used a simulator to train residents on advanced cardiac life support. They found that the use of the simulator dramatically improved the skills of residents as compared to their colleagues who received traditional clinical experience. Jordan et al (2000) find that VR systems improve a student’s ability to visually identify tissue in a body context better than box trainers which contain organs. This visual identification is an important step in reducing the errors that occur in laparoscopic surgery. Grantcharov et al (2003a) find that students trained in VR make fewer errors in real surgery, in addition to reaching proficiency more quickly. As mentioned earlier, VR systems have been shown to be able to identify which residents are “experienced” at a procedure and which are not, creating a basis for awarding certification and reaching graduation (Adamsen et al, 2005). Chaudhry, Sutton, Wood, Stone, & McCloy (1999) show how VR systems can collect measurable error rates that are used to indicate proficiency more objectively than traditional methods of observation.

However, Gerson & Van Dam (2003) conducted an experiment to compare the performance of students trained in bedside sigmoidoscopy to those using virtual reality. They found that VR-based endoscopy training provided inferior training in the students. This study assumed that the bedside practitioners had access to the same patient symptoms that were being presented in the simulator. So there is not unanimous agreement that VR and simulators are effective across the many different procedures that a surgeon must perform.

Gallagher, Richie, McClure, & McGuigan (2001b) recognized that some laparoscopic surgeries require many hours to complete. In such an environment, the surgeon will become fatigued and needs some method to develop stamina similar to that required of athletes. They proposed the use of VR as a form of exercise to develop this stamina.

Game Technology for Non-Entertainment Applications

Historical Applications

Transferring game techniques and tools from entertainment to serious applications like warfare, medicine, health, safety, and science is not a new practice. Perla (1990) describes the evolution of strategy games as both a form of entertainment and a tool for military education beginning as early as 3000BC. This type of dual-use between military and entertainment application has been occurring with board wargames for hundreds of years, with the early cases in Perla's book occurring in the 1600's. Orbanes (2004) describes the emergence of board games based on themes that are popular in society. As business and the stock market became a major part of early 20^{th} century society, these fields showed up in a simplified form as popular board games on banking, investing, and real estate. The most popular and longest lasting of these has been the game of *Monopoly*.

Abt (1970), a former faculty member from MIT, explored the practice of creating board and card games that embody educational content. In 1970 the term "serious games" was coined long before the emergence of computer games and the modern use of that term. Abt's focus was on group-based experiential learning rather than classroom lectures. The shortcomings of the lecture method of learning predate electronic entertainment and researchers have been searching for more interactive forms of learning for decades.

Demaria & Wilson (2004) provide a history of games from pinball in the late 1800's to the computer games of the 1990's. They describe hundreds of games and computer devices that have been influential. The work illustrates connections between different game genres and in the lineage of several high-profile games. The technologies that are adopted for serious games cannot exist without maturing through many products over many years in the entertainment industry. Some of the most unlikely games are often the source of technologies that are necessary to drive games that will be used in medical, military, aviation, and industrial training applications.

Educational Applications

Hutchison (1997), a professor from Simon Fraser University, describes the game of *Healthland* which was introduced to children in the 1920's as a means of teaching public health. The playing board included areas for vegetable farms, fresh air, cold baths, and a "city of safety". The bad areas were labeled "dirtyville", "coffee river", and "tobacco field". The goal of the game was to convey the principles of health and to do so in a manner that was engaging and memorable to children. This interest in the game form did not end with the 1920's, nor is it limited to games using playing boards, cards, and dice. As a Program Manager at the Defense Advanced Research Projects Agency (DARPA), Ralph Chatham (2007) led the DARWARS program which explored the use of computer games as training environments for the U.S. military. The project was motivated by the extensive interest and rhetoric around games within the Department of Defense. Chatham's project found that games could be used successfully for training missions. But, these applications required careful definition of the objectives, design of the scenarios, and assistance from technically proficient users. In general, a military unit could not create a successful training mission using circa 2004 game tools without the help of outside experts. Lenoir (2003), a member of the faculty at Stanford University, further explored the use of computer games as military training devices. He recognized the importance of the games that preceded Chatham's DARWARS Ambush, such as *Marine DOOM* and *Americas Army*. He envisions a time in which soldiers will be able to modify games for their own purposes, though Chatham felt that the toolset available in 2004 could not yet accomplish this.

A committee of experts organized by the Federation of American Scientists (2006a) studied areas that need to be understood before games can become a core part of an educational toolset. Specifically, researchers need to understand what makes it possible to learn specific and targeted lessons within a game environment. This includes the effective embedding of content and the creation of motivation so that students are attracted to the experience. They also recognized that each game will become part of a larger learning environment and that standards for interoperability among games will become important as this area grows. The same organization (FAS, 2006b) created a companion study to identify methods for harnessing video games for learning. The major findings were that: (1) many video games require players to master skills in demand by today's employers; (2) games contain a number of attributes that are useful in learning; (3) there are differences between games for education and games for entertainment; (4) a robust program of research and experimentation is needed because the high development cost for educational games makes it a difficult area in which to attract funding; (5) the existing educational system creates several barriers to the introduction of games and educational organizations need to change their structure to encourage the adoption of new technologies; and (6) outcome data from the large-scale use of games is necessary to determine whether games offer improvements over current methods.

Faculty members at Carnegie Mellon University are interested in using game environments as the context in which universities teach students to write computer programs (Kelleher & Pausch, 2007). Using their *Alice* programming tool they do far more than ask students to write games as an interesting and motivating form of assignment. *Alice* is a graphical storyboarding environment which requires that students learn programming structure in order to layout the characters and actions in a 3D, game-like environment. The goal is not to create games, but to use a game environment as a medium for conveying core principles of computer programming.

Like the *Healthland* game of the 1920's, computer scientists remain interested in communicating medical information via the game medium. Kelly et al (2007) relate their experience in creating a game to teach the functions of the human immune system. They report that the process of playing the game at universities led students to understand the immune system and served as a launching platform for more traditional forms of medical study.

Lane (1995), a professor from the London School of Economics, explores the reemergence of games as a tool in teaching management. This author considers the graphical icons of systems dynamics modeling, such as *Vensim* and *iThink*, to be game environments in which users learn to play with the systems they are modeling. Though pre-dating the current line of computer games, this study does a good job of providing real criticisms and cautions in adopting games. Lane found that the learning results varied widely from one teaching game to another.

Maier & Grobler (2000) studied the characteristics of several popular simulation and modeling tools and proposed a taxonomy for organizing these. This taxonomy begins with modeling-oriented vs. gaming-oriented simulation. The modeling group is subdivided into feedback-oriented continuous simulations which include *Vensim, iThink,* and *Powersim*; and process-oriented discrete simulation models which include *Taylor* and *Simple++*. The gaming category is divided into simulators and planning games. Under this taxonomy, virtual reality medical devices would be considered simulators within the gaming branch of the taxonomy.

Mayo (2007), from the National Academies of Science, believes that there is a crisis in science and technology education. She lays out statistics on enrollment and dropout rates in these areas to emphasize that the supply of science and technology graduates is not sufficient to meet demand. One primary cause of dropout appears to be the lack of quality teaching in the traditional lecture environment. Mayo explores the potential to teach students in a massively multiplayer online gaming environment. Like the lecture hall, it appears to be a very economic delivery tool for hundreds of players who must enter a space simultaneously. However, unlike a lecture, it can be an experiential learning environment as well. NAS is exploring the potential to use online games as educational environments.

Prensky (2006) suggests that children are already learning a great deal about the world by playing games. They learn ethical, team, and goal-oriented behavior from the scenarios presented in games and from the rules that they must follow in order to succeed in those games. He claims that the games provide a medium in which all children can be reached and that no child will be left behind in education. He believes that there is a generation gap between the kids who play games and their parents who worry about and limit this behavior, to the detriment of the child's education.

Zyda et al (2003) describe the activities of the Naval Postgraduate School's Modeling, Virtual Environments, and Simulation (MOVES) program during 2003. The highlight of these activities was the release of the *Americas Army* game. This modification of the *Unreal* game engine remains the largest serious game ever produced and distributed. It has demonstrated to many industries the power of communicating with targeted audiences through the media of gaming. In another paper Zyda provides definitions for the term “serious games” and shows how these have evolved from virtual environments and computer games (2005). As one of the proponents for the *Americas Army* game he uses that as an example of the types of technologies necessary in these games. He creates a hierarchy of applications for game technologies outside of entertainment. This hierarchy focuses heavily on military training, with little detail in the areas of health, public policy, communications, and non-military education.

Finally, Zyda (2007) points out that companies like Electronic Arts and Blizzard produce excellent entertainment titles, but do almost no research and development into new types of games. Since games will generate about $60 billion in revenue in 2007, the author feels that it is important for academia to pickup the R&D mission for this industry.

Business Aspects of Games

The story of the growth of the Parker Brothers game company illustrates the connection between disposable time and money and the popularity of games (Orbanes, 2004). Parker Brothers was built solely on board, card, and tactile games, but their understanding of the consumer’s desire for entertaining distractions was unique at a time when most commercial industry was focused on more “serious needs”. In spite of the high costs of their games, the company found a very large and dedicated market for them.

Sheff (1999) paints a similar picture of understanding the market for leisure and the business environment around the Nintendo Corporation in Japan. The company began as a maker of playing cards, rather than in any form of electronics. Their unique skill has been in understanding the business of entertainment and leisure and they were able to parlay that into an electronic gaming console in the 1980’s. They faced strong competition from Sega Corporation who had a much larger installed base of customers at one time, but were able to overcome this competitor, forcing Sega to exit the game console market. Shankar & Bayus (2003) studied the market network effects between these two companies and found that network size, the number of customers, and network strength were important in this market. Though Sega initially had a larger installed base, Nintendo had a stronger network among its users. They indicate that the creation of a strong network of users is an important contributor to the competitive success of these systems. Schilling’s study (2003) also identified a solid base as being essential to the emergence of complimentary add-on products for the game devices. She noted that an announcement of future releases builds an important air of anticipation around a product. This anticipation strengthens the position of the company in this market.

The computer game business, like the personal computer business, started out with small teams working in their garages and apartments. They had a very small market and only the crudest tools for creating their products (Kushner, 2002). But the popularity of these new forms of entertainment has been so great that they have grown into a multi-billion dollar business. Aoyama & Izushi (2003) estimate that, “Video games and all related industries generated 220,000 jobs and US$ 7.2 billion in wages in the US in 2000”. Their data show a very strong growth curve in the United States with smaller growth in Germany, Japan, France, and the United Kingdom.

Edmonds (2007) provides an analysis of the commercial potential of “massively multiplayer” virtual worlds like *Second Life*, *World of Warcraft*, *Active Worlds*, *Multiverse*, and several smaller products. He believes that virtual worlds are at a stage similar to that of the

World Wide Web in the early 1990’s. Most people are aware of their existence, but do not use them, and are not sure how they would be useful in their own lives or businesses. The author predicts that virtual worlds will grow along a path similar to the World Wide Web, but doubts that the 2D representation of information that is typical of web pages will be displaced by the 3D web. The paper identifies a number of valuable applications of this technology in product development, group collaboration, corporate education and training, military training, marketing and advertising, and direct commerce.

Edward Castronova (2001), a professor from the University of California at Fullerton, explored the economy of online games like *Ultima Online* and *Everquest*. Once a trade in game items emerged on EBay it became possible to determine the value of in-game currencies like gold, manna, and “Linden Dollars” in U.S. dollars. The author determined that the working wage inside these games was approximately $3.42 per hour based on the number of hours required to gather items that could be sold. This showed that the laws of economics could be applied to virtual world economies. Since this publication the connection between in-game currencies and traditional currencies has been solidly established through thousands of purchases and the creation of multiple businesses like IGE.com that serve as brokers between the currencies of virtual and real countries.

Michael & Chen (2005) provide a set of categories in which the non-entertainment use of games is emerging. They suggest that this area contains significant economic opportunity for companies with the right technical expertise. The potential application areas are: military, government, education, corporate, healthcare, political, religious, and art.

Marc Prensky (2001) introduced game-based learning to business audiences with this book. This was one of the first publications to insist that games can really be used for effective learning. He tied together older research into experiential learning and applied it to electronic computer games. Prensky also provides examples of serious games that his consulting firm had created for corporate customers.

Postigo (2003), a professor from Rensselaer Polytechnic Institute, explored the hobbyist game developer who is unpaid for his work and compared this person to the automobile tinkerers of an earlier generation. Though not being paid to modify or create computer games, these hobbyists are generating economic value in that they create products which often lead to the creation of new companies. Unpaid game modifiers are the roots of new companies, new products, and new value. These ideas compliment those of von Hippel (2005) around “lead users” who experiment with products to create modifications that are personally useful. von Hippel casts these users as a form of unpaid and unconstrained R&D lab that companies need to tap into if they want to see the future of their products. The Source Forge web site exemplifies this community of tinkerers in the software and gaming industry. The site coordinates over 170,000 independent projects and 1.8 million users. Scacchi (2004) points out that, though open source is often seen as synonymous with the creation of the Linux operating system, it is also a forum for creating a number of other applications, one of the most popular of which is games. Game programmers are developing habits of chaotic, random, self-directed, and self-coordinated work which are quite different from that used to create software in a corporate environment. This self-directed process is working well in many cases and presents a valuable lesson in alternative methods of software development.

Military simulations have increasingly incorporated game technologies and these tools have served as a disruptive force to traditional product suppliers (Smith, 2007). This has created opportunities for small start-up companies at the expense of larger established firms. This paper demonstrates how game technologies an instance of Christensen's disruptive innovation (1997). As medical education adopts game technologies, the same forces and trends that have occurred in military simulation and training may operate in the medical field.

This model of disruption is also present with the release of a new game console. A new console is an open and obvious attempt to change the balance of profit in the industry. Venkatraman & Lee (2004) studied the release of 2,815 games between 1995 and 2002 to determine the driving relationships between game development companies and the game console manufacturers. They found that a new console typically attracts new development companies who were eager to enter an industry that was previously closed to them.

Games as Technology Products

Bergeron (2006) explored the wide variety of industries that are adopting games as industrial software tools. He explains the history, process, standards, best practices, tools, and designs of the "serious games" that have been developed. By decomposing the game product and process into a number of tools, timelines, and business practices, it is easier to see these applications as packages of software that can be applied to multiple problems beyond entertainment.

Kushner (2002) explores the development of computer games at industry leading id Software, the creator of the *Wolfenstein, DOOM,* and *Quake* franchises. He demonstrates that the creation of advanced computer games really pushes the envelope of what is possible with computers. John Carmack, the founder of id Software, struggled to create products within the limitations of computers from the 1980's to the present. Many of Carmack's games have been called "science projects" because the point of creating them was to demonstrate how far the current generation of personal computers could be pushed toward high-performance virtual reality and game play.

Mayo, Singer, & Kusumoto (2005) have used massively multiplayer online game (MMOG) technology to create a product that they can apply to the military training market. MMOGs do not contain unique graphics or user interfaces. Their differentiating characteristic is in the large server farm that keeps track of a character's actions and assets even after the player has logged out. This enables a persistent, evolving world which can be played or lived over many months or years. For the military this remains a research project to try to understand how the technology can be applied to training, education, and communication.

Computer games have roots in both the military simulation domain and in academic research into virtual environments. Smed et al (2002) provide some distinctions between these three domains and attempt to show how they overlap. Academic research in this area was initially focused on simulation, but then transitioned to virtual environments. Recently, this emphasis has shifted again to computer games. The authors point to a number of fundamental technical problems that have been researched in the past which provide valuable insight into current research in computer games – specifically the interoperability of tools, the reuse of software, and the standardization of data and user interface designs.

Social Acceptance of Games

In spite of their roots in simulation and virtual environments, computer games are generally seen as toys and entertainment for children. These games are not generally seen as a force that is changing the social characteristics of the people who play them. Beck & Wade (2004) borrow a perspective popularized by Don Tapscott in his *Growing Up Digital* (1998) by claiming that the current generation of game players has a very different personality, mental perspective, set of expectations, and means of working with others. Beck and Wade attribute this to experiences with computer games and suggest that, in the future, businesses must learn to adapt to the traits of this generation as they enter the workforce. They specifically point to the generation's ability to take risks, multitask, and provide leadership in groups that form across a network. They claim that these people are committed to building teams and to winning contests because that is the primary activity that they experience and that is reinforced in game environments. This implies that incoming medical students may be more competitive than their predecessors and they may be more accepting of game technologies in their school and professional lives.

Nolen Bushnell (1996), the founder of Atari and creator of early games like *Pong* and *Asteroids,* explores the role of games in the larger business of computer equipment development and sales. He envisions a time in which games are a larger part of all electronic devices, accessible from the traditional computer, console, and arcade machine – but also in the kitchen, as an electronic pet, and as a universal interface to the home. Written in 1996, he correctly predicts the rapid growth of the number of game users and the impact on other industries.

Herz & Macedonia (2002) present two perspectives of the impact of computer games on society. Herz explores civilian society, while Macedonia explores military training. Herz describes the social ecology of games that build networks of competitive players and shared spaces for discussing the game and receiving products from the supplier. He discusses the addiction of players who return to a persistent online game like *World of Warcraft* because it is a changing social space that includes the player's input just as effectively as any social group in the physical world. Macedonia explains that the military has been interested in using games for training since the 1970's and continues to explore its application as new technologies emerge. He predicts a time in which games will be nearly as widely used by military organizations as they are for entertainment.

Rosen & Weil (1995) explore limitations on the use of technologies due to technophobia. They find that the fear of or low comfort level with technology is more prevalent in older adults, those with low incomes, and minorities. The study is also corroborated by a study by Dell Computers that found that 55% of the population is "technophobic". One of the major barriers to technology is found to be the poor interface provided to the user of the devices. The user interface is one of the primary strengths of the computer game and may be an avenue through which technophobia can be reduced in society. Average members of a society need a non-threatening conduit through which they can approach all kinds of devices and tools.

Squire & Steinkuehler (2007) treat massively multiplayer games as social environments and ask what it means to be literate in such a society. They focus on the emergence of unique phrases and abbreviations that emerged in the *Star Wars Galaxies* game immediately after its release. Within a few weeks of the game going public, a number of complex standards for communication emerged. These often focused on the desire of the players to remain in character, communicate accurately with the group, and establish their own status as an experienced player. The authors argue that literacy in the real world does not imply literacy in these virtual worlds. Newcomers to these environments find that they cannot understand many of the conversations because they make reference to events that occurred prior to their entry or they adhere to standards that have been worked out through hundreds of hours of conversations. Therefore, there is a unique literacy in these games and it requires experience and study to achieve personal literacy in these new societies.

Steinkuehler (2005a) presents massively multiplayer online games as a social “third place”. In *Bowling Alone*, Putnam described how America was losing most of its third places for socialization (2001). Steinkuehler suggests that the in-game activities carried out by players is more social than it is action-oriented. In the process of playing the game, the players are creating a social bond, a special club, and a tribe similar to face-to-face groups in the physical world. She suggests that this is important in the field of education because this virtual tribe represents a big part of the identity of students and the values that they hold. In order to convey knowledge to them, such knowledge must be relevant to their social networks, which are increasingly built in multiplayer games. Steinkuehler also demonstrates that though entertainment media like television and computers do encourage a withdrawal from social interactions, the participation in online MMOGs creates new social networks in which people are active participants (2007). She concludes that online players experience a very different social dynamic than a lone computer user, Internet surfer, or single-player gamer.

Dissertations on Computer Games

Doctoral level dissertations have been written on the educational, social, technical, and economic impact of games in society and on individual people.

Social Impacts

David Clearwater’s dissertation (2006) comes from the department of art history and communication and focuses on the military’ use of computer games as a medium of propaganda and political manipulation. The author maintains that most people in North America have never experienced real war and must take many of their beliefs about it from the media. Previous generations received these impressions from movies, books, and television. The newest generation is receiving that picture from video games. This work focuses on games that are used for public relations, rather than those that are used to train the military itself. Most prominent of these games have been *Full Spectrum Warrior* and *Americas Army*. The first of these was an experiment in the training value of computer games and was also released as a commercial product. The second was created as a recruiting tool and later migrated into military training applications.

Garrelts (2003) suggests that video games are an expression of the norms and values of our society and that a formal framework for discussing the content of the games is needed. He proposes a grammatical model to dissect video games and an approach to labeling the rhetoric of video games and the story that they present to orient and motivate the player. The grammar consists of objects, interactions, player responses, video scenes, and gamer input – the first three of which are hierarchically decomposed. He applies this grammar to three games in the *Final Fantasy* series to demonstrate how it is useful in understanding, categorizing, and studying the actions and messages in a game.

Nichols (2005) explores video games as a medium of social communication. He is interested in the benefits that video games offer to society as a new medium for the communication of ideology and the construction of social norms. He explores the means that have been used to move video games from their niche customer base to a larger mass market, achieving legitimacy through social adoption and through their relationships with other forms of media. The dissertation describes the structure, organization, relationships, and labor conditions within the video game industry.

Steinkuehler (2005b) explores the literary and social activities that occur within MMOGs. She finds that multiplayer gaming is not socially isolating, but is rather extremely social and requires that players develop multiple relationships and manage those toward the achievement of a number of desired goals. Within the clans or guilds of these games there are many social constructs that must be maintained and the activities that are conducted to accomplish these are very similar to those that occur in a physical social club or professional association. She also establishes that these games present a new third place in which people are not required to play their role as a member of the family (the first place) or as an employee of an organization (the second place). Instead this is a third place that allows them to define their personality, behavior, and responsibilities to meet their own need for expressiveness and to join with others who are doing the same. The study counters the reports in the popular media that game players are isolating themselves, losing their literacy, and engaged in activities that have no value in the physical world.

Whitlock (2004) reexamines the relationship between theater and computer games. She notes that more recent games have borrowed a number of ideas and devices from the theater and these significantly improved the storytelling and engagement of the video game. She suggests that every game is a theater performance that evolves in real time and may not be repeatable. These experiences provide the story setting that is characteristic of theater, but they also allow the viewer to play an active role in the story, rather than remaining a passive observer of the actions of others.

Williams (2004) explores the often reported negative impacts of games - specifically increased aggression and reduced social connections. Their study of the *Asheron's Call 2* game finds no evidence of increased aggression and mild negative changes in sociability. They also find an increased level of community spirit and activism. Like Steinkuehler, they found that social structures develop within the gaming environment.

Educational Applications

Robison (2006) examines computers games as a medium for literacy. Working with a dozen game designers she develops an understanding of the desire to create games that are specifically meant to be a dialog between the designer and the player and among multiple players. Following from the work of Steinkuehler which showed that massively multiplayer games are a very rich environment for reading and writing; this author steps into the world of the designers to understand their process for creating an environment that encourages and empowers this online literacy. She does not distill a single common process for designing these types of games, but instead shares the perspectives of the dozen designers that she studied and explains their actions through the research in literacy.

Vaupel (2002) showed that video games had no impact on the level of cognitive performance of fourteen children in her study group. She measured cognitive performance using tests both before and after playing video games. Her focus was on the purported negative impact of games on the minds of children. The study was not designed to measure any positive learning from the games themselves, but merely to determine whether it interfered with traditional forms of learning.

Business Aspects of Games

Nair (2005) develops an economic model of the optimal pricing strategy for video game products. He finds that consumers anticipate the future decline of prices of new games and postpone purchases to reduce their costs. He proposes a pricing strategy for the distributors of games that allows them to maximize profits by minimizing consumer decisions to postpone a purchase. The study is based on cost data for 500 games released for the Playstation console between 1998 and 2000, and the subsequent discounting of those game prices.

O'Conner (2001) noticed that people who are confined to wheelchairs have very few opportunities for exercise and experience significant declines in their cardiovascular health and increases in their weight. He experiments with the "Game(Wheels)" system and gathers data on its effects on cardiovascular health and user opinions about the system. The "Game(Wheels)" device is a combination of the treadmill, stationary bicycle, and video game controller. It allows people to exercise using their own wheelchairs in their own homes. The author finds positive impacts on health and positive attitudes toward the adoption of the device.

Yu (2004) demonstrates that higher levels of visual vividness, interactivity, and creative approaches within a game increase buyer attractiveness to the game. The product characteristics that are identified are presented as a framework to assist designers and marketers in creating and selling games.

Technology in Games

Wainess (2006) proposes that navigation maps will aid game players in navigating a 3D space inside of a game. He suspects that the players are faced with a number of cognitive tasks and that the navigation map will reduce the cognitive load and allows the player to perform other tasks more efficiently. The result of his experiments was that the navigation maps did not have a positive influence on the players' performance in the game. The author suggests some reasons for these disappointing results, primarily associated with the low cognitive difficulty of the space the players were asked to navigate in the experiment.

Zaparyniuk (2006) shows that video game playing improves the ability of players to perform sequencing, non-verbal, and cognitive tasks. These improvements accrued to both experienced gamers and those who were newly introduced to computer games in order to participate in the study.

Simulation

John Casti is a member of the Santa Fe Institute and explores the scientific uses of models of the real world (1997). He presents these tools as a new form of laboratory for understanding complex systems that are difficult or impossible to study in a more traditional lab. His models are applied to understanding social networks, growth in nature, and the behavior of crowds. In one experiment he used the computer game *Football Pro 1995* to predict the winner of the 1995 Super Bowl. He does not maintain that the game could predict the score; merely that it may contain enough information to identify which team has an advantage that could indicate the winner. But he does speculate on a future in which such a game may be accurate enough to provide a more reliable prediction of the outcome of a specific game.

Clark Dodsworth (1998) created one of the first compilations of material on simulation and virtual worlds which combined the technical and artistic details of both entertainment and military systems. He did not use the term “serious games”, but took an early step in considering computer games as tools with equal validity and power to military simulations.

Salah Elmaghraby, a professor of Operations Research at North Carolina State University, identified five major application areas for simulation in a paper published in 1968. These were: (1) as an aid to thought, (2) for prediction, (3) communication, (4) experimentation, and (5) training. After forty years, these categories remain nearly comprehensive in their scope.

The use of simulation as a form of entertainment did not occur to this author and has emerged as a new category with the availability of powerful personal computers.

Lane, Slavin, & Ziv (2001) reviewed a large number of simulations that have been used for medical training. These included video, CD-ROM, actors, mannequin, and computer-based systems. They acknowledge that simulators play an important role in teaching because they provide exposure to consistent problem sets and allow immediate feedback on performance. The latest simulators combine computers with mannequins that have animatronic capabilities. The high cost of mannequins suggests that lower-cost devices could be created using the same human body models in the computer, but linking these to a computer animated patient.

Duncan Miller, a researcher at MIT, and Jack Thorpe, the Air Force officer who managed the Simulator Networking (SIMNET) project, provide a summary of the creation of the military's first major virtual simulator that networked multiple cockpits together for interactive training (1995). The SIMNET program is recognized as the direct ancestor of most current networked, man-in-the-loop virtual training devices. The principles of networked simulation described in this paper remain part of the foundation of all current simulators.

Mike Zyda led a committee of simulation and entertainment experts in evaluating the potential to use movie and game technologies in military and other government simulations (National Research Council [NRC], 1997). The study concluded that it would be to the military's advantage to create a research institute which explored the technologies used in movies, sound studios, and games and to direct these toward problems in military training and education. The study led to the formation of the Institute for Creative Technology at the University of Southern California in 2000. Nearly a decade later another National Academies study group concluded that the Department of Defense should invest in research focused on computer games for training and simulation of military problems (NRC, 2006). They believe that tackling the issues associated with building the hardware and software infrastructure necessary for large games, as well as the representation of cognitive behaviors, would be directly applicable to some important issues in military training.

Michael Schrage, a researcher at MIT, casts many forms of experimentation as simulation and demonstrates how successful companies have used this type of simulation to understand what customers need, to prototype new products, and to break perception barriers within their companies (Schrage, 2000).

History of Technology

Warfare is the most catastrophic event within human societies (Boot, 2006). It results in the loss of life, property, philosophy, revenue, and self-respect. Because it has such a huge impact on individuals and society, every form of technology is adopted and incorporated into weapons or tools of war. This includes gunpowder, metals, electronics, chemicals, atomic power, biological agents, medical expertise, sociology, psychology, mathematics, and the basic sciences. Engineering and management are the methods by which these are applied in large organizations and toward large endeavors. There appears to be no such thing as military technology simply because every technology is adopted and used militarily – which would include those developed for entertainment such as moviemaking, television transmission, computer networks, and computer games. Since medical and health issues are just as crucial to the health of society, we should expect to see this area adopting technologies from many outside domains just as the military does.

Ancient cultures, buildings, and agriculture were all impacted by an understanding of astronomy. Rather than limiting its application to planting, societies incorporated this knowledge into their buildings, religious practices, and social organization (McClellan & Dorn, 1999). It appears that any technology that is accessible to the entire population will be adopted and applied toward some means that is important to the adopter, even when that application is far from the original purpose of the technology.

The Greeks and Romans primarily applied technology to machines of war (Klemm, 1991). But Hero of Alexandria reversed this application trend in the first century A.D. by creating life sized mechanical puppets that could dance in the gardens of rich princes. Twenty centuries ago technology for entertainment was directed at the rich. Today modern entertainment technology is riding on the disposable time and wealth at many different income levels in society. Klemm also notes that in antiquity labor of all kinds, including the application of machinery and technology, was considered the work of slaves. Citizens avoided all involvement with labor and perhaps stifled the potential for social advancement by refusing to engage in work that would create machines to improve productivity. Though this attitude does not exist in most Western societies, it does remain in others, perhaps to the detriment of their own growth.

The automobile industry in Britain had definite roots in the bicycle industry. The centers of British automobile manufacture in the early 20th century settled in Coventry and Birmingham specifically because these were the centers of bicycle production and the places at which rolled tubing for frames and inflatable tires were being manufactured (Cardwell, 1972). The bicycle became both a device for transportation and entertainment, perhaps an early mechanical parallel to the dual-use of entertainment technologies by the military and medical communities today.

In a later book, Cardwell (1995) notes that technologies are often developed in support of sports and leisure and then flow back into other parts of society. One example was the invention of the fuel injection engine for sport racing cars in Germany in the 1930s. Similarly, the leading edge of ski and mountain climbing technologies is focused on sporting applications and then flows back into industrial and social uses such as logging and mountain rescue. Sports in general appear to be an early stereotype of the type of technology adoption that is now occurring in the computer and software domains, including entertainment products. Advanced countries have invested significantly in sporting equipment, which has led to the emergence of large companies to serve this demand. These companies are compelled to invest their profits in R&D if they are to remain ahead of competitors who seek to provide a performance advantage to the professional and amateur athletes who use the equipment. The results of this research are products that can cross market boundaries and expand into new areas.

Pursell (1981) contrasted the early use of the automobile in Europe with that in America. In Europe, this new machine was dedicated to luxury and entertainment – the touring automobile. But upon arrival in America, Henry Ford used mass production to turn the vehicle into a practical family, business, and farm transportation machine. This was an early example of the conversion of a machine for entertainment into one for more practical day-to-day tasks, similar to the nascent “serious games” transformation that is happening in several industries now.

During the 20^{th} century there were two major waves of technology into the home – electricity and appliances (Pursell, 1995). The electrification of rural communities in the 1920s made it possible for homeowners to convert many of their existing machines so that they were powered by electricity. Household tasks like pumping and heating water, refrigerating and cooking food, and lighting and fanning the house became much less labor intensive. The second wave came in the 1950s following World War II. The industrialization of America, created a wide variety of new home and office appliances which could transform the way work was done. Households added comforts for their homes in the form of electric stoves, air conditioners, fans, freezers, shavers, waffle irons, radios, and dozens of similar devices. These household devices improved both the comfort and the productivity of the home, significantly reducing the amount of work required to operate it. Computers and games, like the radio and television before them, have continued to make the home a comfortable and stimulating environment. They also reduce the amount of labor required to gather information and improve the level of education available in the home.

Don Tapscott claims that the current generation is developing some very powerful and useful behaviors through their use of the computer and the Internet (1998). He lists fierce independence, emotional and intellectual openness, a sense of inclusion, the free expression of strong views, and a spirit of innovation. He claims that these traits will change society and business as this generation enters the workforce and progresses up through the ranks. Beck and Wade (2004) added computer games to the list of experiences shaping the generation. Both believe that these people will cause fundamental shifts in the way business works by incorporating the traits listed above.

In his later *Wikinomics* (2006), Tapscott explores the effects of “Web 2.0 applications” such as Wikipedia, MySpace, Flickr, Second Life, YouTube, Linux, and the Human Genome Project. He believes that the generation using these see themselves as the creators of information and knowledge, rather than simply as consumers. As economic value becomes more founded in digital information, the country with the most digital creators will have a significant advantage in the world. Tapscott paints a picture in which people are able to be more productive and innovative when they work according to their own rules and in their preferred environment, rather than entering the traditional corporate space.

Carlson & Goldman (1994) point out that medical advances have made possible some extremely complicated forms of surgery. Preparing for, controlling, and monitoring these activities has become a challenge. They suggest that in addition to medical devices, virtual reality technology may be very useful in improving performance in some of these complex procedures.

Solow (1957) presents an aggregate production function that identifies the forces that generate increased productivity in an economy. Using data from 1909 to 1949, Solow concluded that gross output per man-hour doubled in that forty year period. He also showed that 87.5% of that increase was due to technical change and that the remaining 12.5% was due to the use of capital. This indicates that technology in its various forms is the most essential ingredient in increasing the output of labor. In the medical field, the shortage of teaching faculty is a major bottleneck in the productivity of the system. Solow's Nobel Prize winning concept may indicate that this situation can only be changed through the application of technology and not through the adoption of new processes or methods of teaching in the old manner.

Disruptive Innovation and Creative Destruction

Kuhn (1970) points out that science does not evolve smoothly from old ideas into new ones. Instead it requires a revolution in which older ideas and established practitioners are overthrown by newer ideas. In many cases, new ideas are scorned and suppressed by the ruling intelligentsia. Only when a new idea can be shown to solve existing problems that are unsolvable by the current methods or theories does enough support gather to allow them to emerge as the generally accepted ideas. However, writers of scientific history usually smooth over the revolutions and present the progress of science as a smooth and continuous growth of ideas, which is far from the actual truth.

Hart & Milstein (1999) argue that incrementally improving the performance of a product will be overcome by Schumpeter's creative destruction. They point out that the greening of a product to make it more environmentally friendly is an incremental innovation and is not a sustainable approach to competition. Sustainable competition searches for ways to disrupt an industry and recreate it in a more efficient form. Virtual reality and game technologies are potentially one of these disruptive innovations.

Perelman (1995) compares the writings of Schumpeter and Wells to illustrate the similarities in their theories and the differences in the vocabulary that they use to express their ideas. Most notable is Wells' insistence that modernization and progress depend upon the destruction of social and economic structure that previously worked well. Without this destruction, society will not have the necessary human and financial resources to create more productive approaches to emerging problems.

Rogers (1995) explored the diffusion of new ideas and new products across a number of countries. He was most interested in the rate of spread of an idea and what dampens or accelerates that spread. He created the popular categories of innovators, early adopters, early majority, late majority, and laggards in adopting new products or ideas. Some of the innovations he described are the sanitation of water, methods for rice farming, and the use of hybrid corn seed. He identified five determinant variables that impact the rate of adoption: (1) perceived attributes of the innovation, (2) type of decision required, (3) communication channels used, (4) nature of the social system, and (5) the extent of the change agents' promotional efforts. The patterns identified by Rogers and the factors for adoption may apply directly to the adoption of computer game technologies by new industries.

Reinganum (1985) uses extensive mathematical models to demonstrate that higher investment in the current phase of development of a product shortens that phase and leads to the next phase in which better products appear. Because incumbents have the least to gain by shortening the current phase and have the highest risks in moving into the next phase, they invest the least in innovations. Though they have more resources to invest, incumbents have less motivation to invest. A challenger is much more aggressive in investing in innovation because change is to their advantage.

Smith, Ferner, & Grimm (2001) show that a new entrant into a market can gain an advantage by rapid and repeated changes in products, processes, marketing, and branding. These changes move the market away from its current equilibrium. Because incumbents are usually reluctant to change the current situation they are less likely to press for change. In this environment the new entrant can initiate a pace of change that keeps the incumbent in catch-up mode. Their study focuses on the impact that Nike had in unseating Reebok as the leading provider to sports shoes in the late 1980s and early 1990s. They show that the same occurred in Wal-Mart's moves to overtake Sears and in Home Depot's moves to overtake Lowe's during that same period.

Modern products and services have become extremely complex. As a result it is very difficult for a single company to master all of the disciplines necessary to introduce a new product or to significantly improve on an old product. Chesbrough (2003) suggests that innovation leaders must learn to open up their processes and practices and to build partnerships for innovation. Companies must find others who complement their own weaknesses and build partnerships that are beneficial to both. These partnerships may involve suppliers, customers, academics, and even competitors. Companies that insist on tackling all problems with internal resources will find themselves lagging behind those who use an open innovation model to leverage the strengths of other organizations.

Christensen (1997) points out that a small company can enter a market on the back of a technology which has very limited initial capabilities. He shows how this has allowed new entrants to capture the low-profit end of the market for metals, construction equipment, and computer hard drives. However, in some cases the base technology contains the potential for significant improvement in performance that is desired by the market. When this occurs the small competitor is in a position to capture an ever increasing share of the market from large established companies. In many cases, an established company cannot justify the investment in a lower performing technology and will be unprepared to compete as these new technologies improve their capabilities. The dilemma is that there is little that an established company can do to protect itself from the potential of every new technology that may be important to future products or services in their field.

Hargadon (2003) argues that innovation is generally a recombination of existing ideas and technologies. In order to create truly unique products and services, companies need to bring together people and expertise from multiple domains that are very different. Individuals need to be conversant in multiple disciplines in order to escape the dogma of a single specialization. Bridging two domains allows people to pursue solutions that are outside of the prescribed ideas and approaches of a single field. Applying computer games to other industries has been an instance of this bridging of domain ideas.

Leonard (1995) explores the concepts of core competencies as introduced by Prahalad and Hamel, but focuses instead on a potential weakness of these. She points out that companies may turn core competencies into “core rigidities” by insisting on sticking with the strengths that have been successful in the past. She suggests that a company must be able to see generalizations of their competencies in order to adjust to changes in the market environment. In some cases, it may also be necessary to completely abandon competencies when they have become completely irrelevant. The medical education field is one of the most rigid in preserving practices that have been in place for decades. This community has been described as transforming their practice only once every century (R. Satava, personal communication, February 22, 2008).

von Hippel (2005) has studied the impact of “lead users” on the development of new features for products. He has discovered that these high-performance, high-demand users purchase products and then modify them to extend their performance. He has studied these users in windsurfing, mountain biking, and open source software. They are effectively an external R&D lab for the company’s products. von Hippel argues that they need to be enrolled as partners in identifying and developing features for the next generation of products. Three criteria must exist for this to happen effectively: (1) the users must have an incentive to innovate, (2) they must have an incentive to reveal their innovations and share them, and (3) their work must be at a competitive level with innovations created internally and by competitors.

Chapter 3: Conceptual Framework and Research Method

Both Joseph Schumpeter (1976) and David Wells (1889) described the undeniable forces of creative destruction in society and industry. They explained the need for new ideas, processes, products, and technologies to replace those that have been dominant in an industry for decades or centuries. Wells was particularly interested in the economic benefits that accrue from these changes. He maintained that, over time, most industries create an over capacity for their products or services. This consumes both financial and human resources that are not being applied productively. Creative destruction eliminates some of this capacity and releases the resources to be deployed toward more productive applications (Perelman, 1995). In his 1992 Harvard dissertation, Clayton Christensen created a modern model of these forces and extended them to explain disruptive innovation. He focused on advances in the computer hard drive industry and showed how small start-up companies had repeatedly captured the market from larger, more established companies. In many cases the established companies had achieved their leadership by disrupting a previous leader, but were unable to recognize the same forces when they were being exerted upon them by a new group of small start-ups.

Solow’s Nobel Prize winning ideas on the cause of productivity growth in industry and society showed that technological change was responsible for 87.5% of these economic improvements (1957). The adoption of computers by every industry has been one of the major forces driving productivity over the last fifty years. These devices were initially applied to computation for scientific projects and financial reporting. They were then applied to administrative tasks of record keeping and communication across global enterprises. More recently computers have been applied to great effect to improving education. Computer-based training, web-based training, online courseware, simulations, virtual reality, and computer gaming have all used available technologies to increase the productivity of the education process.

Wells, Schumpeter, Christensen, and Solow all recognized that there are many opportunities for the reallocation of revenue and profits when changes occur in society. These changes may be triggered by shifts in the weather and the natural environment, by a new set of social mores, by the discovery of new resources, or by the creation of new technologies. In the last century, the latter has been the most dominant source of change. New technologies and the products that are created to leverage these offer opportunities for people and organizations to improve their financial and social positions. Given such an incentive, many people will make an attempt to use these new technologies and will work vigorously to persuade others to use their products. In this dissertation I am examining this phenomenon around the application of virtual reality and computer gaming technologies to medical education and training.

Medical education is one of the socially necessary and important areas in which very little computer augmentation has been applied. Satava maintains that major changes occur in this field only once every century (R. Satava, personal communication, February 22, 2008). The last of these was the introduction of the apprenticeship model of education at the beginning of the 20th century. The social demands to educate more physicians and surgeons, and to provide them with a larger base of expertise than ever before, are forcing the medical education system to consider alternatives to traditional forms of training. It appears that the introduction of modern computer-enabled training tools is a necessary change in medical education, and perhaps the “change of the century” that Satava describes (R. Satava, personal communication, February 22, 2008). Simulation, virtual reality, and computer game technologies have been adopted with great success in other educational fields and offer similar advantages to medical education.

Virtual reality and game technologies may be a budding disruptive innovation in medical education. They have been applied with some initial success in a few niche areas of medical practice and education, specifically anesthesiology, minimally invasive surgery (a.k.a. endoscopic and laparoscopic surgery), and cardiac care. In this section I present a conceptual framework around the evolution of medical education to show how and why these technologies are valuable and effective improvements.

Conceptual Framework

I propose the medical education model shown in Figure 6 as representing the progression of methods of teaching surgical skills over the last century.

Human	**Animal**	**Box Trainer**	**Mannequin**	**Simulation**	**VR/Game**
Learn on humans: Living patients, the newly dead, and cadavers	Learn on animals: Living and newly dead pigs, cats, and others	Learn on organs in a box: Human-shaped box contains organs, tissue, or test devices	Learn on a physical replica: A full-body device with synthetic skin, organs, and fluids	Learn on an animated machine: Includes computer, hydraulics, pneumatics, and electrical responses	Learn on computer images: Mathematical models, visual images, sounds, and some tactile feedback
Advantage Exact Replica, Existing OR	Advantage Similarities, Availability	Advantage Availability, Convenience, Human Shape	Advantage Human Shape, Logistics	Advantage Rich Experience, Multi-Function,	Advantage Rich Experience, Flexibility, Low Cost
Disadvantage Scarcity, Single Use, Ethical Issues	Disadvantage Anatomy, Single Use, Social Mores	Disadvantage Not Alive, Single Use, Animal Organs	Disadvantage Static, Lacks Realism	Disadvantage High Cost, Complexity	Disadvantage Screen-barrier, Nontactile
Examples Cadavers Live Patients	Examples Porcine Labs	Examples MIC-Trainer	Examples CPR Annie	Examples Sim One HPS	Examples MIST-VR LapSim

Figure 6. Medical education model

Reznick & MacRae (2006) have included several of these forms of training in their analyses of the current state of medical education. Many of these methods have been created and adopted in parallel, but there is a progression of complexity and dominant use in education as shown in the model. The figure includes a short summary of the training method, its advantages, disadvantages, and an example. Figure 7 provides a photographic version of the model.

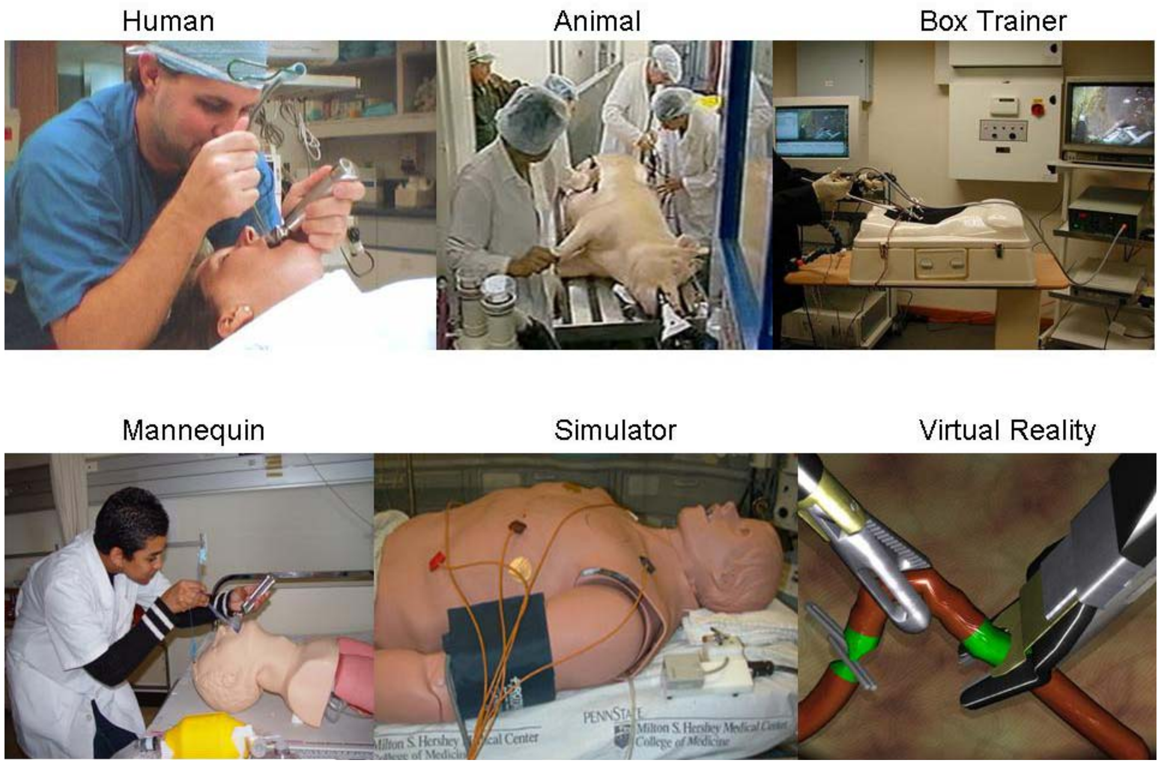

Figure 7. Medical education model by example

The literature suggests that medical education has been evolving to serve the needs of surgical practice. Surgeons initially practiced a small number of open surgeries and learned the skills to accomplish this through an apprenticeship model in which they observed and assisted an accomplished surgeon in the procedures (Flexner, 1910). The subjects for operations at that time were primarily patients that were undergoing surgery and occasionally extended to the newly dead. As the preservation of bodies became more advanced, cadavers were added to the teaching curriculum. Today, cadavers are considered as a unique medium from the newly dead because of the effort required to preserve the body, the procedures for preparing it for an educational session, and the significant differences between it and living tissue (Roach, 2003). The tissues of the newly dead are much more similar to the living, with the primary difference being the lack of circulation, respiration, and neurological response. The advantage of learning on humans begins with the identical nature of the subject to future patients. Though there are unique features of many human bodies, each is nearly identical to the others. Modern surgical researchers have suggested that different categories of bodies require experience with that category – specifically men, women, children, the obese, and those with deformities (Satava, 2005c).

As surgical procedures became more complex and refined it became necessary to practice them more frequently than could be accommodated through available human subjects, both living and deceased. The need also emerged for a medium that can support experiments with new procedures, tools, and drugs. This led to the wide-spread adoption of animal labs within teaching hospitals. These provided the facilities to deliver animals on demand for education and experimentation, significantly freeing the educational process from the limits imposed by human subject availability. Porcine subjects have many features similar to humans, serve as an acceptable surrogate, and are often referred to as the "gold standard" for education and experimentation (Rick Wassel, personal communication, March, 16, 2008). Though pigs and other animals have similarities to the human anatomy and are significantly more accessible, the differences in their anatomy remain a hindrance to learning many details of human surgery. In most operations, the animal is also a single use subject. A procedure may be performed only once or a few times before the tissue or organ is no longer appropriate as a teaching medium. For example, the removal of an organ can only be performed once on an animal. The repair of a major artery in a limb may be performed four times, one on each limb (Ritter & Bowyer, 2005). In most cases, the educational session is a terminal event for the animal (Seymour, 2005). At the conclusion, the animal's body must be disposed of and another acquired for additional lessons. Evolving social mores increasingly restrict or entirely prohibit the use of live animals in education. In the United Kingdom, for example, it has been illegal to use living animals as subjects for surgical education since 1926 and other European countries impose limitations on the practice as well (Waseda et al, 2005; Moorthy et al, 2006, Kitching, 2008).

Many operations do not require access to an entire human or animal cadaver. In these cases, organs or tissue harvested from animals are preserved and used inside of a "box trainer". This category of devices is so named because of the original practice of placing organs inside of a box that represented the body cavity. The box has evolved and taken many forms, often being shaped like a human torso and closed with a rubber or silicon skin to make it appear more realistic. These closed torsos have also become popular for laparoscopic surgery in which small incisions are made in the skin and the surgeon must learn to operate with the barrier of human skin between him and the object of surgery. These boxes may also contain simple devices that are designed to test the dexterity of the surgeon and provide a practice environment in which to develop specific skills such as manual dexterity, tool use, or object location. When using real organs, these devices have many of the same disadvantages as animal and cadaver methods. The organs can only be used once to teach a procedure. The organs are not alive as would be a porcine or human subject, so do not respond appropriately to surgical procedures. Social restrictions remain when dealing with human and animal organs, but are much less stringent than when using living animals.

Mannequins have been used for centuries to illustrate the human body and to practice basic procedures. But, modern materials like rubber, latex, and silicon have made it possible to create mannequins that are as pliable as human tissue and that can be manipulated and cut in a realistic manner. These devices may include fluids that represent those inside the body and which may be under pressure or circulating so that they respond appropriately to cuts, punctures, and injections. These devices have the advantage of taking human shape and having some degree of human texture. The logistics of managing the devices is much simpler than for cadavers, animals, or organic tissue. Preservation, refrigeration, sanitation, and disposal are much less difficult problems. The disadvantage is that mannequins have never been alive and do not posses the complex features of living tissue. Modern materials are very useful, but fall short of being able to accurately represent all of the properties of the human body.

Mannequins were the basis for a new category of devices that is more dynamic. The incorporation of pneumatics, hydraulics, electronics, and computers inside of a mannequin has created simulators that provide much of the animation and dynamics that are present in living subjects but missing from mannequins and box trainers. Devices like Sim One in 1967 and the more recent Human Patient Simulator (HPS) attempt to replicate the dynamic response of a patient to surgical procedures and to accurately present symptoms that can be used for diagnostics. The first of this class of trainers was the Sim One anesthetic simulator described in an earlier chapter. This device incorporated all of the engineering mechanisms listed above and has been referred to as “a device ahead of its time” because the techniques used remain part of simulator designs thirty and forty years later (Abrahamson, 1997). These devices provide a rich experience which can be programmed to give specific responses. The number of unique responses in the HPS product is currently in the hundreds. These simulators are considered to be very expensive learning devices, often costing $100,000 to $200,000 each. This limits the degree to which they can be applied. They are also complex mechanical devices to configure and maintain. Vigorous use of the devices can lead to breakdowns of the electronic, hydraulic, pneumatic, or mechanical parts of the system.

Virtual reality was introduced into medical training in the 1990’s by Richard Satava and Jaron Lanier. They applied the newly invented head mounted display and data glove to surgical training in 1991 and there have been many more advanced systems since then (Satava, 1993). These systems attempt to represent the patient as a computer generated, virtual object. The goal is to provide the realism of living tissue and response without the limitations of the physical mannequins and simulators. These systems are generally less expensive than simulators and can be very flexible in the procedures that they can replicate. However, they suffer a “screen barrier” where the student is on one side of the computer screen and the virtual patient is on the other. This is the first category of educational method that does not allow the student to physically touch and manipulate a real world object. Advances in VR are adding tactile or haptic feedback devices in which a mechanical actuator is used to resist movement where the body tissue resides in the virtual space. VR systems are also being combined with mannequins and simulators in an attempt to provide a realistic tactile environment.

This dissertation explores the advantages and potential adoption of technologies emerging from the computer gaming and entertainment industries. These have already been applied to numerous medical training devices. However, in most cases, the term “game” is not acceptable in this domain. Instead these technologies are referred to as virtual reality and are considered an extension of the VR devices that emerged from university research labs in the 1990’s. Some researchers have also suggested the term “microsimulation”, which is sometimes used in military training to refer to systems based on computer games. This separates these technologies from VR and vaguely acknowledges their roots in the computer game industry (Binstadt et al, 2007). However, the medical literature seems to indicate that referring to game technologies as a form of virtual reality is preferred in the medical community.

Rationale

Throughout the review of the literature there were repeated references to the similarities between learning surgical skills and learning in other “high hazard” professions, meaning professions that pose a risk to human life (Ziv et al, 2003). Most notable of these was the comparison with the use of virtual reality to train pilots in both commercial and military aviation (Issenberg et al, 2007). These pilots are entrusted with the lives of millions of people annually and are expected to master a complex set of skills to be able to perform their jobs competently. Pilot training has incorporated simulators since the early 1930’s when Edwin Link created the “pilot maker” device for the Army Air Corps (Rolfe & Staples, 1986). Since then these devices have evolved into much more complex computer-driven systems that leverage the latest technologies for instrument replication, algorithms for aircraft physics, motion platforms, three dimensional visualization, and team-based training procedures. During the seventy years in which aviation training has used simulation and virtual reality, the medical profession, specifically surgeons, have continued to learn their skills through an apprenticeship model that relies heavily on living human patients and surrogate animals. There has been little progress in adopting new learning technologies in this field as has occurred in many others. The numerous analogies presented by medical researchers in the literature point toward core similarities between aviation and medical education which suggest that virtual reality would be a very beneficial technique.

Given the established organizations, methods, and results for medical training, there appear to be two overriding factors that could compel such a large industry to adopt technologies that are already available and have been proven in other fields – reduced costs and reduced medical errors. If new technologies like virtual reality could be shown to provide comparative and acceptable results at a significant cost saving, then there would be a strong motivation to break down long established barriers to the use of virtual reality systems (Issenberg et al, 2005). Medical schools are supported by both state educational funds and hospital operating revenues. The pressure to reduce both of these is already being felt in the amount of exposure that residents can get to hands-on, faculty-led training opportunities (Satava, 2004). If virtual reality systems can reduce the cost of preparing a resident to become an independent medical provider, then we may expect to see established practices changing to adopt these tools and methods.

The second major motivating factor would be the reduction of medical errors. Error is a real part of all professions, but is significantly important in "high hazard" professions like surgery. Society and the medical profession itself have become very focused on the number of medical errors inflicted on patients every year. These errors have been measured as the eighth leading cause of death in America (Agency for Healthcare Research and Quality [AHRQ], 2003). If simulators and virtual reality can reduce medical error and patient fatality, then this would seem to be a technology that cannot be ignored. Established traditions of training are partially responsible for the number of errors that occur. Traditional methods are based on the assumption that it is acceptable for residents to practice and develop their skills on live patients. Under this philosophy, the greater good to society overrides the immediate risk to a single patient. But, pressure is mounting to examine these methods and to find ways to teach residents without incurring risks to live patients.

Finally, it is clear in the literature that student access to specific symptoms has always been a critical issue in the quality of their medical education. In fact, the lack of such opportunities in previous centuries led to the practice of body snatching to provide newly dead corpses for medical education (Roach, 2003). The opportunities to access the wide variety of cases that will face a practicing surgeon are very small and unbalanced. Students may be exposed to hundreds of cases of one symptom and none of many others. Relying on residency and apprenticeship cannot guarantee any specific level of access to and practice with the wide variety of symptoms that must be mastered. However, like the flight simulator, a virtual reality system could present a specific array of symptoms, provide repeated access and practice, and measure performance until competency is reached (Ritter & Boyer, 2005). Simulator/virtual reality-based training may allow the student to achieve proficiency and to matriculate more quickly and with a set of skills that have been objectively measured rather than subjectively observed.

The broad body of literature that was analyzed and the conceptual framework that emerged point toward the primacy of these types of issues with the current medical education system, and led to the following hypotheses as the basis for this dissertation.

The Hypotheses

The conceptual framework suggests that medical education will continue to be impacted by the power of computers, 3D animation, and user interface devices. The literature reviewed earlier suggests that virtual reality and computer game technologies are best applied to education in laparoscopic surgery because of the existing intermediation between patient and surgeon caused by the camera, computer monitor, and long rod effectors used during surgery. Therefore, I have constructed the following hypotheses that are focused on the use of these technologies specifically for laparoscopic surgical education and training.

Hypothesis 1: Training in laparoscopic surgery can be accomplished at a lower cost using virtual reality and game technology-based tools than through existing methods of training.

Hypothesis 2: Virtual reality and game technology-based training environments provide better access to representative patient symptoms and allow more repetitive practice than existing forms of training.

Hypothesis 3: Virtual reality and game technology-based training environments can reduce the training time required to achieve proficiency in laparoscopic procedures.

Hypothesis 4: Virtual reality and game technology-based training can reduce the number of medical errors caused by residents and surgeons learning to perform laparoscopic procedures.

The hypotheses suggest that the advantages of applying game technologies to medical education are significant enough to lead to their adoption as a widely accepted form of training just as each of the previous methods presented in the model above. Indications of this adoption and evidence of its continued progress have been collected from the published literature on computer game technologies, the application of these outside of entertainment, the use of virtual reality for medicine, and trends in medical education.

Research Method

The evidence in this dissertation focuses on the experiments and the adoption of medical VR systems which include computer game technologies. I have collected and analyzed over 200 published papers and books which contain information around the disruptive effects of new technologies on established industries, and the specific changes that are occurring around the use of VR in medical education. The material in the literature review and throughout the research analysis is drawn from the domains of:

- Medical education,
- Virtual reality,
- Simulation,
- Computer game technologies,
- "Serious games",
- History of technology,
- Disruptive innovation, and
- Creative destruction.

Of necessity, this study must focus on a specific type of medical education and the adoption of a specific VR system. Simulators have been widely adopted for education in anesthesiology, cardiac trauma, and laparoscopic surgery. Of these three, the latter is seen as the most amenable to VR technologies because the surgeon is already separated from the patient by a "screen barrier". Laparoscopic surgery is typically carried out with a micro-camera inserted into the body cavity and the images displayed on a computer monitor. Therefore, the imposition of a VR image in this environment does not change the visual stimuli to the surgeon. The surgeon's hands are also removed from proximity to the patient's body by long-rod instruments with miniature effectors on the ends. This is also similar to the controls provided by a VR system.

Laparoscopic surgery is an operation in which open surgery is replaced with small incisions in which one, two, or three microsurgical instruments are inserted. These instruments are accompanied by at least one micro-camera that can deliver images of the tissue and the instruments with which the surgeon is operating. These images are displayed on a computer monitor and are the primary visual feedback to the surgeon. Laparoscopic surgery reduces the degree of surgical trauma experienced by the patient, which in turn reduces the opportunity for infection, surgical time, recovery time, and collateral damage to the body. A more complete definition is provided in the following textbox.

Webster's New World Medical Dictionary definition:

Laparoscopy: A type of minimally invasive surgery in which a small incision (cut) is made in the abdominal wall through which an instrument called a laparoscope is inserted to permit structures within the abdomen and pelvis to be seen. The abdominal cavity is distended and made visible by the instillation of absorbable gas, typically, carbon dioxide. A diversity of tubes can be pushed through the same incision in the skin. Probes or other instruments can thus be introduced through the same opening. In this way, a number of surgical procedures can be performed without the need for a large surgical incision. Most patients receive general anesthesia during the procedure.

The advantages of laparoscopy include a shorter post-operative period with less pain. The avoidance of a large abdominal incision also decreases some of the post-op complications related to the heart and lungs. In addition, there is decreased mortality with some laparoscopic procedures, as compared to the old open surgical procedures.

Laparoscopy was long used by gynecologists for the diagnosis of diseases of the ovary and uterus. Removal of the gallbladder by laparoscopic techniques was introduced in the late 1980s. Fiber optic instruments and video cameras now allow procedures on the smallest of structures and the use of laparoscopy has been extended to surgical procedures involving the appendix, colon, uterus, repair of hiatal hernias, and more.

Laparoscopy comes from two Greek words. The first is lapara, which means "the soft parts of the body between the rib margins and hips," or, more simply, the "flank or loin." The other Greek root is skopein, which means "to see or view or examine." Skopein has become -scope in English.

Source: http://www.medterms.com/script/main/art.asp?articlekey=6211

There are a number of laparoscopic surgical training systems available from commercial providers, to include:

- AccuTouch or LaparoscopyVR, by Immersion Medical;
- LAP Mentor, by Simbiotix;
- LapChol, by Xitacts;
- LapFast, by Verefi Technologies;
- LapSim, by Surgical Science;
- MIST-VR, by Mentice; and
- ProMIS, by Haptica.

All of these share similar characteristics and possess unique individual features. This study does not attempt to make any qualitative differentiation of the products. I chose one of these as the subject of this study based on the large number of published papers and evidence that it is the most widely used in medical schools and seminars. The Minimally Invasive Surgical Trainer – Virtual Reality (MIST-VR) was initially developed by Rory McCloy and Robert Stone. In 1995 they founded Virtual Presence Inc. to market the system. However, their company used all of its capital before making a financial success. The company and the MIST-VR patents were purchased by Mentice AB which is headquartered in Gothenburg, Sweden. Mentice also purchased the force feedback patents of Xitacts and combined them with the MIST-VR product.

The resulting product is now marketed under the name Procedicus MIST to match their corporate product naming convention (personal communication with Miles Kitching, June 12, 2008).

All of the publications on the use of this system continue to use the original MIST-VR name of the product, so that is the name used throughout this dissertation. The system has been widely used in scientific studies to determine whether it is effective at teaching laparoscopic skills. I was able to collect nearly fifty published research papers on the results of these studies and experiments. Brunner et al (2005) reported that 40 of 253 general surgery residency programs in the United States had at least one unit as of 2005. These facts led me to select MIST-VR as the system with the most objective scientific analyses of its capabilities.

In the medical literature it is the practice of researchers to identify the manufacturer of specific devices used in experiments along with the location of the company. Researchers also provide a statement about any association that they have with that company. Keeping with this practice, I state that I have no affiliation with any of the companies that make laparoscopic trainers and no personal interest or investment in these companies. MIST-VR was chosen as the focus of this study purely because of the large body of scientific studies that could provide objective data for this dissertation.

MIST-VR was introduced in 1995 and has been the subject of studies for over ten years. The system consists of a personal or laptop computer, visualization software, replicas of laparoscopic instruments, a mounting device that holds these instruments in positions approximating actual surgery, and a skills progression curriculum. Figure 8 provides two typical photographs of the MIST-VR system. Table 1 provides the computer specifications for several versions of the system that were cited in the published studies.

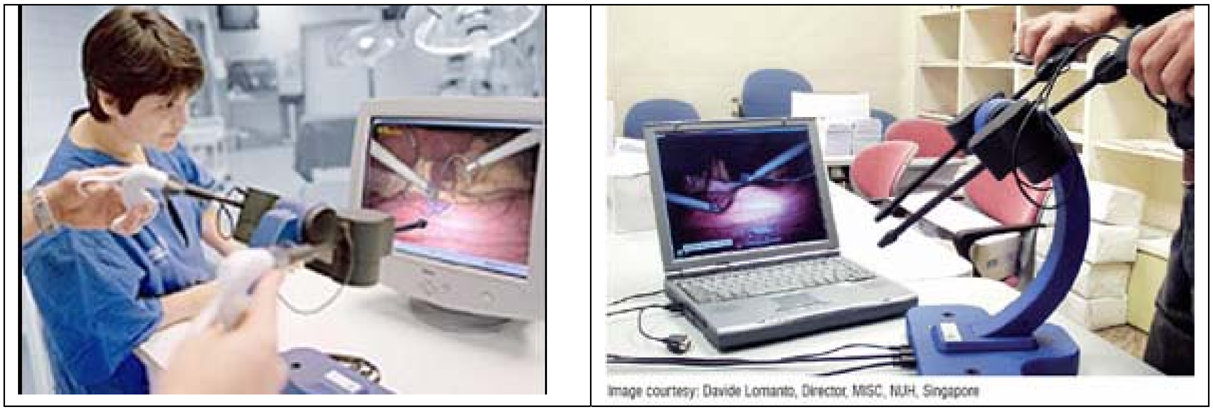

Figure 8. Minimally Invasive Surgical Trainer – Virtual Reality (MIST-VR) system

Table 1. MIST-VR implementations used in the literature

Version: 1.0	**Version: 1.2**	**Version: 2 and Procedicus**
Source: Jordan et al, 2000; Gallagher et al, 2002; Grantcharov et al, 2001	**Source:** Seymour et al, 2002; Gallagher et al, 2001b	**Source:** Mentice Web Site
Location: Queens University, Ireland; Aarhaus Univ, Denmark	**Location:** Yale Medical School, USA; Queens University, Ireland	**Location:** Mentice AB, Gothenburg, Sweden
Computer Specs: Windows 95 200 MHz Pentium I 32MB RAM Mystique 4MB Graphics 15 frames per second 17” Color Monitor	**Computer Specs:** Windows 98 400 MHz Pentium II 64MB RAM Matrox 8MB Graphics 15 frames per second 17” Color Monitor	**Computer Specs:** Windows Vista Dual Core Laptop 256MB RAM Nvidia 128MB Graphics 30 frames per second 17” LCD

Source: various identified in the table

This system qualifies as “game technology-based” because of its use of a 3D rendering engine, the incorporation of physical models of the body tissues, and its portability on a laptop computer. It also has the potential to be networked so that multiple students can work in the same space. Like many specialized entertainment games, MIST-VR, makes use of specialized controllers instead of the keyboard and mouse. Flight simulators use joysticks; racing games have steering wheels, stick shifts, and brake/gas pedals; dance games use sensor pads on the floor; and music games use guitars, drums, microphones, and piano keyboards. Similarly, MIST-

VR uses a specialized controller that represents the camera and surgical instruments typical of laparoscopic surgery. These connect to the computer through the USB port in the same manner as the game controllers listed above.

When experimenting with the value of MIST-VR for conveying medical skills to students, most researchers conducted a scientific test with clearly established objectives, control groups, objective measures of performance, and a statistical analysis of the results. Studies were usually incremental, seeking only to add one small piece of provable information to the body of knowledge in this area. I found the studies to be carefully designed, incremental, formulaic, and interested in concrete results. The researchers were not generally given to hyperbole or grand statements about the global potential of game technology, virtual reality, or computer-based training devices. They preferred to make a single smaller assertion that was backed up by their study.

I collected over 50 papers on experiments done with MIST-VR and over 100 papers on more general topics in medical education and minimally invasive surgery which have some application to the hypotheses proposed. The literature was so voluminous and covered so many different ideas that I created a coding scheme to classify the contents of each paper and to associate it with the hypotheses. This allowed me to apply all of this data to the questions of interest without becoming lost in the large number of details.

Reference Coding

The references collected were coded so that they could be grouped and organized when addressing a specific hypothesis. The reference coding was done as a spreadsheet in Microsoft Excel and a sample of that is shown in Figure 9. The complete reference coding matrix is provided as an appendix at the end of the dissertation. The matrix is divided into four sections, one for each hypothesis. Within each section, the references are ordered alphabetically by primary author. Most references applied directly to the hypotheses, but others unveiled assumptions about medical training that are prevalent in the community. Some also point to future work that needs to be done to fully quantify or qualify virtual reality as a training system and as a case for future business growth.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Hypothesis 1: Training in laparoscopic surgery can be accomplished for significantly lower costs																	
Aggarwal	2007	X		X		X				X	X						VR training shortens the learning curve, reducing both cost and time in education.
Bridges	1999	X								X							Learning in the OR is much more expensive than learning in VR

Figure 9. Medical VR coding matrix.

Each of the coding categories is shown in Figure 10 with a very brief description.

Group 1: Hypothesis Addressed
H1 = Cost of Training
H2 = Access to Symptoms
H3 = Time to Proficiency
H4 = Error Reduction

Group 2: Medical Specialty
L = Laparoscopic Surgery (including arthroscopic, endoscopic, and minimally invasive)
M = MIST-VR (specific mention of this laparoscopic VR training device)
A = Anesthesiology (including airway management)
C = Cardiac Care

Group 3: Nature and Content of Reference
S = Scientific study was conducted
D = Specific device is used or referenced
G = Game technology is specifically referenced
F = Futuristic, Visionary, or Speculative discussion of medical education
Ed = Educational methods are described
B = Background information that is useful
Eth = Ethical issues are explored

Figure 10. Medical VR reference coding items.

The first group of codes is associated with the four hypotheses of this study. These indicate whether the paper had any information that contributed to the hypotheses in either a positive or a negative manner. Many papers contained data that contributed to more than one hypothesis. In the complete matrix in the appendix, papers that contribute to more than one hypothesis are included under each hypothesis section of the spreadsheet.

The second group of codes indicates the medical specialty that is addressed in the paper. “L” indicates laparoscopic surgery. “M” indicates a specific reference to the MIST-VR device. “A” indicates the use of virtual reality or simulators for education in anesthesia and airway management. “C” indicates the use of these devices in cardiac care. Some of the first simulators were applied to anesthesia, so some very good background material is available in this specialty. Some of the newest computerized mannequins provide a system that can be used for a number of different treatments, including anesthesia and cardiac care. These references provide information that indicates the growing use of computerized systems, though not necessarily virtual reality.

The third group captures information about the nature and content of the reference. “S” indicates that the paper includes a scientific study with statistically analyzed quantitative results. “D” indicates the use of or reference to a specific training device. I used this information to create a list of all simulator or virtual reality devices in the literature analyzed. This list is also included as a separate appendix to the dissertation. “G” indicates the presence of a technology that is derived from computer games for entertainment. “F” is a futuristic, visionary, or speculative view of the field. In many cases, researchers who have published earlier scientific studies will write these types of papers after they have established their scientific reputation. “Ed” refers to the medical education process, curriculum, or philosophy. “B” indicates that the paper has useful material for the background of this study. These were very useful in the introduction and problem statement sections of the dissertation. “Eth” indicates ethical issues surrounding medical education. These generally concern the treatment and safety of the patient or the use of live animals as surgical subjects.

Finally, the coding matrix includes a comment field in which I capture a statement about the paper that I want to incorporate into the thesis or that can be used as shorthand to identify the contents of the paper.

Chapter 4: Data Analysis, Results, and Conclusions

Data Analysis

The collected papers on the use of MIST-VR and supporting information in medical education present the capabilities of the system to improve medical training in a number of areas. Each experiment and the published results tend to focus on a single aspect of the system. However, improvements in one area often suggest corresponding improvements in another. For example, a reduction in the cost of providing training, may also suggest that these lower costs will allow more frequent access to the training because more systems can be purchased. Measured reductions in the error rates that occur in laparoscopic surgery, tend to suggest that there will be a corresponding reduction in the costs associated with remediation or insurance premiums. If a system allows faster progression through the educational curriculum, this can also reduce the cost of providing the education to a student or to an established surgeon. So the analysis associated with one of the hypotheses presented can draw from material that is central to another hypothesis. In this section I attempt to clearly examine the support for each hypothesis separately without traveling too far into the supporting data for another hypothesis.

Hypothesis 1: Lower Cost

Hypothesis 1: Training in laparoscopic surgery can be accomplished at a lower cost using virtual reality and game technology-based tools than through existing methods of training.

Many hospitals use the operating room as the theater for training students, either while performing surgery on live patients or as a location for familiarization with roles and equipment. Brunner et al (2005) observes that this is a very expensive learning environment and becomes a significant limiting resource. Bridges & Diamond (1999) have conducted a study on the costs associated with teaching students in the operating room (OR) which emphasizes the inordinate expenses associated with this approach. They estimate that teaching a resident in the operating room across a four-year residency adds $47,970 to the cost of the education. These costs are purely derived from the fact that it takes longer to perform a surgery when using the event as a teaching opportunity. Absent this teaching function, the facilities and personnel could be applied to additional revenue generating procedures. The authors estimate the cost of using the operating room at $257.40 per hour. However, Frost & Sullivan (2004) estimate the cost of the operating room at $1,500 per hour and Hyltander (2003) maintains that a Swedish operating room costs $1,000 per hour. Richard Satava cites the cost as “$250 per 15 minutes” (personal communication, May 20, 2008). If these authors are correct, then Bridges and Diamond’s estimates are too low by tens of thousands of dollars. Using the ratios of the costs given by the different authors this number could be between $186,363 and $279,545 across a four year residency.

The Accreditation Council for Graduate Medical Education (ACGME) and the American College of Surgeons (ACS) have both observed that traditional methods of education do not contain objective measures of competency and that new teaching methods are needed to measure and certify such competency. This concern has fueled interest in computer-based training as an environment that is both affordable and in which objective performance metrics can be collected (Brunner et al, 2005).

Training in MIST-VR has demonstrated its cost effectiveness in eliminating the need for faculty instructors. The preprogrammed set of scenarios that come with the system present progressively more difficult tasks and require only the aid of a research assistant to set-up the system and answer questions (Brunner et al, 2005).

Frost & Sullivan, a strategic consulting firm for technical companies, was commissioned by Immersion Medical to determine the Return on Investment (ROI) for the AccuTouch laparoscopic trainer (also marketed under the name Laparoscopy VR), a system very similar to MIST-VR (Frost & Sullivan, 2004). This study was conducted through interviews with 237 medical professionals to identify the cost factors for training laparoscopic surgery and the changes that occur when AccuTouch is included in the training program. My own analysis of the data provided in the survey is shown in Table 2. The AccuTouch system costs $72,000 per unit. After the first year there is also a $324 monthly service fee to keep the system up-to-date and to repair any malfunctions or broken instruments. They also estimate that it requires 40 hours to setup the training program for the system, at a cost of $75 per hour. Finally, the cost of physical space to locate the simulator is $1,000 per year. This results in a one-time cost of $72,000 per system and a first year operating cost of $4,000. In the following years, the operating cost is $4,888 for the maintenance fee and the facility space. Assuming a four year life of the system, this is a total cost for the system of $72,000 + $4,000 + 3($4,888) = $90,664. This is an average annual cost of $22,666. This assumed four year life of the system correlates with the typical four year residency of a medical student. This allows some alignment between the size of an incoming class and the number of simulators that must be available to support them and the residents already in the program.

The Frost & Sullivan study (2004) provides estimates of cost savings in the following categories:

- Time Savings,
- Reduction in Errors,
- Faster Time to Competence,
- Equipment Breakage Costs, and
- Other Financial Benefits.

Time savings is by far the largest contributor to the financial advantages of using the system. They estimate the elimination of 6.4 instructor hours each month at a cost of $75 per hour. This is an annual saving of $5,760. As with other studies they find that students trained on these simulators perform real operations more quickly once they become part of the staff of the hospital (see Hypothesis 3 for a more detailed analysis of this effect). They estimate that a trained student can perform 104 additional procedures per year and that each of these procedures generates $1,100 in revenue. This accumulates to $114,400 of additional revenue from these students every year at the conclusion of their four year residency.

Reduction in errors. The survey provided opportunity for the respondents to estimate the cost of errors that could be eliminated through the inclusion of the simulator. They estimated that a single facility generates 16 surgical errors per year and that each of these costs the hospital $500. However, the survey respondents did not feel that any of the errors with which they were familiar could have been avoided through the use of the simulator. This does not correlate with the literature collected around hypothesis 4 in this dissertation. But it will not be added as a cost reduction in this section.

The survey did however estimate that simulators could contribute to a reduction in the number of cancelled procedures due to insufficiently prepared staff. The respondents felt that four cancellations could be avoided each year, thus saving an expense of $850 for each. This is a cost saving of $3,400 annually.

Faster time to competence. Some teaching hospitals use their residents to perform revenue generating procedures. In these cases, bringing a resident to proficiency more quickly can create opportunities for the hospital to earn money more quickly. In the Frost & Sullivan survey, hospitals had an average of 26 residents who were learning basic laparoscopic surgery. Respondents estimated that each of these would be worth an additional $750 in annual revenue if they could be brought to proficiency within three months. This could potentially create $19,500 in revenue for an average resident population.

Equipment breakage cost. Teaching hospitals in this study allocated an average of $27,143 per year for repair to real laparoscopic equipment. They estimated that training with a simulator could reduce breakage costs by 5%, or $1,357.

Other financial benefits were identified by the respondents. The largest of these was that organizations that had purchased the simulator were able to generate revenue with the system by selling time on it to other teaching programs that did not have their own device. This resulted in an average annual revenue stream of $23,250. Second, they estimate that they eliminated $1,100 per year in other forms of training that were replaced by the simulator.

Summarizing the investment in a simulator with the cost savings over a four year residency and into a fifth year of practice, the return on investment is $246,642 at the conclusion of the fifth year (Table 2). The authors of the study found that an investment in the system paid for itself in 169 days.

Table 2. Cost/benefit of an AccuTouch laparoscopic simulator.

Category	Description	Fixed Cost	Recurring Over Residency (4 Years)	After Residency (5th Year)	Total over 5 Years
Investment	AccuTouch Simulator	(72,000)	(18,664)	0	(90,664)
Time Savings	Instructor time		23,040	0	23,040
	Additional Procedures		0	114,400	114,400
Reduction in Errors	Complications		0	0	0
	Cancellations		13,600	0	13,600
Faster Time to Competence	Residents generating revenue		78,000	0	78,000
Equipment Breakage	Reduction due to better training		5,428	5,428	10,856
Other Financial Benefits	Reduction in alternative training		4,400	0	4,400
	Revenue from selling time on simulator		93,000	0	93,000
	Total Cost/Benefit	**(72,000)**	**198,804**	**119,828**	**246,632**

Source: Original calculations by the author based on data in Frost & Sullivan, 2004

These costs are derived from a survey of users of the AccuTouch laparoscopic simulator. That system is very similar in cost and capability to the MIST-VR system that is the focus of this study. Therefore, though specific numbers may change, the categories, trends, and magnitude of savings could be similar for MIST-VR and other competitive systems. This data indicates that a laparoscopic simulator is a very cost effective investment because of the many different positive effects that it has on the operating revenues of a teaching hospital.

McNatt & Smith (2001) extend this by citing cost savings through the complete removal of live animals from the early stages of learning laparoscopic skills. It appears that the surgeons and researchers who conduct studies in this area are well aware of the cost items associated with surgery. As practitioners they can readily identify the removal of animals, cadavers, and animal tissue in training (McClusky et al, 2005; Hamilton et al, 2002). They also appear to have some appreciation for the fixed costs necessary to maintain the delivery of these resources. But, none have conducted a concrete study of the costs similar to the Frost & Sullivan study. Costs can be identified by category and estimated based on various data points given across the literature. Table 3 identifies some of the major cost categories associated with each form of training. The table includes quantitative measures of these costs where they were available, though many papers identified a category of cost without giving any specific financial information.

Table 3. Cost categories associated with each method of psychomotor training.

Method	Major Cost Items	Cost ROM	Rate	Source
Humans	Cadaver Acquisition	$1,850	each	Tabas, 2005
	Cadaver Disease Testing and Shipping	$500	each	Roach, 2003, p.151
	Cadaver Storage Facilities	$10	each	Time, 1937
	Cadaver Preparation (Freeze and Thaw) and Sanitation	n/a		Frezza, 1999
	Cadaver Disposal	$15	each	Kastner, 2004
	Operating Room	$1,500	per hour	Frost & Sullivan, 2004
	Operating Room (Sweden)	$1,000	per hour	Hyltander, 2003
	Operating Room (minimal cost)	$257	per hour	Bridges & Diamond, 1999
Animals	Live Animal Acquisition	n/a		Kitching, 2008
	Live Animal Shipping	n/a		
	Live Animal Storage Facilities	n/a		
	Live Animal Anesthesiology	n/a		
	Live Animal Veterinarian	n/a		Kitching, 2008
	Live Animal Preparation and Sanitation	n/a		
	Live/Dead Animal Disposal	$22	each	Kastner, 2004
	Operating Room	$1,500	per hour	Frost & Sullivan, 2004

	Operating Room (Sweden)	$1,000	per hour	Hyltander, 2003
	Operating Room (minimal cost)	$257	per hour	Bridges & Diamond, 1999
Box Trainer	Animal & Human Organ Harvesting	$50	each	Sedlack et al, 2003
	Organ Shipping	n/a		
	Organ Storage Facilities	n/a		
	Organ Preparation and Sanitation	n/a		
	Organ Disposal	$1	each	Kastner, 2004
	Box Device Cost	n/a		
	Box Device Supplies (synthetic skin, organ mounts)	n/a		
	Operating Area	$1,000	per year	Frost & Sullivan, 2004
Mannequin	Mannequin Cost	$2,200	each	Limbs & Things web site
	Surrogate Leg for military testing	$5,000	each	Roach, 2003, p.151
	Replacement Parts	n/a		
	Maintenance Contract	n/a		
	Storage Area	n/a		
	Operating Area	$1,000	per year	Frost & Sullivan, 2004
Simulator	Simulator Cost	$40,000	each	Binstadt et al, 2007
	Replacement Parts	n/a		
	Maintenance Contract	n/a		
	Simulator Facility	$250,000	each	Marshall et al, 2001
	Facility Maintenance	$10,000	per year	Marshall et al, 2001
	Simulator Operations – Electricity	n/a		
	Storage Area	$1,000	per year	Frost & Sullivan, 2004
	Student Trainee Fee	$500	each	Frost & Sullivan, 2004
VR	VR System Cost	$72,000	each	Frost & Sullivan, 2004
	Maintenance Contract	$4,000	per year	Frost & Sullivan, 2004
	VR Operations – Energy	$7	per year	PC World laptop test
	Operating Area	$1,000	per year	Frost & Sullivan, 2004

Sources: various identified in the table

This table illustrates the high costs that are reported for simulators and virtual reality in the literature. However, these costs are generally for reusable assets rather than disposable ones. Traditional education with cadavers and animals requires the repeated acquisition of the training platform and the use of facilities appropriate for biological specimens and waste, as opposed to the lower cost of facilities appropriate for electronic equipment.

Under Hypothesis 4 we explore the reduction in errors due to the use of MIST-VR, but those studies also included cost factors associated with the errors. Specifically, they identified longer operating room time, complication rates, and conversion to "open laparoscopy" as costs created by low levels of psychomotor skills. MIST-VR has been shown to reduce all three of these factors and hence the associated costs (Grantcharov et al, 2003a). Korndorffer et al (2006) conducted a survey in which he learned that 88% of the laparoscopic surgeons surveyed believed that VR skills labs were effective at improving operating room performance and reducing the events listed above. They also point to Scott's study (2000) indicating that training-specific devices provide better training at a lower cost than learning in an operating room with live procedures.

Studies of medical errors in general have identified these errors as the eighth leading cause of death in the United States with between 44,000 and 98,000 people dying as a result of medical error each year (Cohen et al, 1999). The estimated cost associated with these deaths is $37.6 billion (AHRQ, 2006). This demonstrates the magnitude of the problem of surgeons with inadequately developed skills. Laparoscopic surgery accounts for just a fraction of these errors and a smaller portion of deaths. However, studies have shown that laparoscopic surgeries have an error rate three times higher than that of traditional open surgery and that these numbers did not improve over a ten year period in which laparoscopy was gaining popularity (Huang et al, 2005). Therefore, the use of any device that can reduce errors will also lead to valuable reductions in costs.

Current trends in medical training call for a shift from knowledge-based education to proficiency-based education. Traditional curriculums have required that residents pass tests of their knowledge and experience a specified number of hours of practicum and apprenticeship.

However, there has been no objective measure of the skills that are acquired under these programs. Computer-based training systems have the ability to measure many aspects of the performance of the resident and to use that as a means of determining skill levels. Collecting such data in live procedures has been shown to be very labor intensive and costly, while doing so with computerized systems like MIST-VR is much less difficult and less costly (Derossis, 1998).

Finally, Rosser et al (2007) determined that commercial video games could be used as a testing tool to predict which residents would have the best initial laparoscopic skills. Based on these findings, he suggested that custom video games could be offered as an inexpensive and readily available tool for developing base psychomotor skills.

The literature clearly indicates that practitioners believe that the cost of VR trainers is lower than the use of live tissues. The data collected here provides some measure of the magnitude of these savings based on multiple categories of costs and rough estimates of their size. There remains a need for research that includes both medical and financial experts that are in a position to capture exact costs of the curriculum at a medical school and teaching hospital.

Hypothesis 2: Better Access

Hypothesis 2: Virtual reality and game technology-based training environments provide better access to representative patient symptoms and allow more repetitive practice than existing forms of training.

Embedded in much of the literature surrounding methods of training is an assumption that the established methods can provide sufficient and equal access to the symptoms required to drive the education process. Changes in the complexity of medical procedures and in the social environment surrounding medicine challenge this assumption more aggressively every year (Cooke, Irby, Sullivan, & Ludmerer, 2006 and McClusky et al, 2005).

> The traditional Halstedian apprenticeship model of 'see one, do one, teach one' is no longer adequate to train surgeons, since good laparoscopic skills cannot be developed by merely watching an expert. Laparoscopic proficiency is only realized after sufficient practice in the minimally invasive environment. To this end, a variety of approaches have been developed to teach laparoscopic skills outside of the operating room; these methods include practicing on animal models or artificial tissues, training boxes, and virtual reality simulators. (Pearson et al, 2002)

Pearson (2002) goes on to cite six benefits of using a VR simulator for training:

- Objective assessment of surgical skills,
- Decreased risk to patients as surgeons progress along the learning curve in VR rather than in OR,
- Simulation of any type of case or complication imaginable,
- Standardization of residency training regardless of the type of patients that present to each teaching hospital,
- Experimentation with new procedures in a safe environment, and
- Ability to practice an operation on patient-specific anatomy prior to the real operation.

The first two of these are important to hypothesis four on reducing errors, but the latter four all speak to issues of access to specific symptoms prior to practicing on a live patient. Grantcharov et al (2003b and 2004) believe that repeated practice of procedures, standardized tasks, and objective measurements are important factors in mastering laparoscopic skills and that these are all lacking or limited in traditional OR-based training. They go on to cite studies that quantify the number of operations that must be performed to achieve proficiency. For cholecystectomy both of Grantcharov's papers and that of MacFadyen, Vecchi, Ricardo, & Mathis (1998) indicate that this number is between ten and thirty surgeries. Under current teaching methods these learning events must occur on animals or live patients. VR systems allow these to be moved off of patients, significantly reducing errors where they matter the most, and off of animals. These reduce both the errors on human patients and the costs of procuring and disposing of animals.

Cooke et al (2006) observes that the knowledge base for medical practice has "hypertrophied", that the methods for delivering medical care are much more complicated, and that the expectations of the public are higher now than when the current apprenticeship model was described in the Flexner Report in 1910. These all call for changes in the means of delivering education and specifically in creating opportunities for residents to access the wide variety of symptoms that they will face and the diversity of procedures that they must master in practice.

McClusky et al (2005), Brunner et al (2005), and Eastridge et al (2003) all point to the important impact that new professional regulations and legal restrictions have on resident training. In most areas there are now regulations or laws that limit the number of hours that a resident can spend in the hospital - currently a maximum of 80 hours per week, with proposals to reduce this to 60 hours per week. These regulations are intended to reduce medical errors due to the exhaustion of residents. However, they also reduce the opportunities for a resident to observe or participate in a surgery when a patient presenting specific symptoms arrives at the hospital. Previously, residents competed to experience as many operations as possible, which led to extended hours at the hospital, lack of sleep, degraded judgment, and increased medical errors. The reduction in working hours leads to a reduction in errors, but also results in less experience with live patients. This loss of training must be compensated for in some other form of instruction. VR offers one solution and incorporates technologies that improve every year, pointing to continuing improvements in the future.

Aggarwal et al (2006) believes that it is now generally accepted that students must learn their laparoscopic skills prior to entering the operating room, specifically through practice on animals, the use of box trainers, and the use of VR trainers.

VR trainers are uniquely well suited for experiments that explore new methods of teaching or the effects of adverse conditions on performance. Ali et al (2002) and DeMaria et al (2005) have both used the devices for such experiments. Ali was able to expose high school honors students to laparoscopic surgery through the MIST-VR device. Such exposure would have been impossible with animal or box trainers. His goal was to measure the effectiveness of laparoscopic training methods on an audience who had no previous exposure to surgical procedures, something that is very difficult when working with residents who possess varying levels of procedural experience. DeMaria et al conducted experiments in which residents on night call were pulled into the hospital with little sleep and asked to perform laparoscopic surgeries in VR. They wanted to determine whether such night calls resulted in more errors in procedures. This experiment could have been conducted with animals and box trainers, but would have been considerably more costly and necessary coordination would have significantly limited the extent of the study.

McClusky et al (2005) observed that the new emphasis on reducing medical errors will make practice on live patients impossible in the near future. They observe that with VR simulators, students can practice as often as they like, there are objective measures of performance, and there are no recurring costs of materials. Other authors have added that the simulation laboratories can be staffed with student assistants rather than full faculty members (Brunner et al, 2005; Eastridge et al, 2003). McClusky et al also expressed a preference for MIST-VR because of its wide availability, reliability as a teaching tool, consistency in presenting symptoms, and validity in evaluating surgical skills.

Resnick et al (1993) estimate that judgment comprises 75% of a successful operation, which is primarily made up of knowledge that was received didactically. They estimate that technical skill comprises the other 25%. Unfortunately, they believe that current methods of medical education have focused on the prior while ignoring the latter. VR-based simulations are specifically focused on the perceived weakness in developing these technical skills.

Pham et al (2005) conducted studies in which they compared student opinions on the use of MIST-VR to a newer system called “RapidFire/SmartTutor”. They found that both systems improved the skills of students and that the students preferred the use of the newer system. It is encouraging that progress is already underway in improving the usability of these devices while maintaining their effectiveness in training.

Swedish surgeons believe that it is impossible to offer residents enough exposure to mentors and experience in real operating rooms (Hyltander, 2003). They conclude that VR provides automated mentoring integrated with simulated operating experience. They feel that these systems are an important part of the future of training in technical skills.

Because laparoscopic surgery is relatively new, as of 2001, many surgeons were receiving their laparoscopic training through two or three day short courses. Each of these is offered through independent organizations that deliver Continuing Medical Education (CME) and have no standard curriculum, approach, or certification criteria. Each hospital must then determine whether to allow the CME trained surgeon to practice the procedures in their facilities based on the courses that can be completed (Jordan et al, 2001; Korndorffer et al, 2005; and Kothari et al, 2002). Many of the VR systems that could be used in these CME courses come with a standardized curriculum and tools to measure performance which would provide a foundation for hospital acceptance of trained surgeons in these procedures (see the section on hypothesis 3 for more details on this).

Unlike live surgeries or infrequent animal operations, VR and box trainers allow repetition of the same procedures until proficiency is achieved. A resident may be able to work through a specific set of skills multiple times in an afternoon. The computer-based VR systems go a step further by allowing automatic data collection and measurement during the procedures. Studies have indicated that students using these simulators improve their performance and reduce their errors in future live operations (Madan et al, 2005a; Madan & Frantzides 2007; Maithel et al, 2006). This type of repetition is impossible, impractical, or unaffordable in all other forms of training.

A unique use of a simulator or virtual reality is as a tool for evaluating the skills of job applicants. A system like MIST-VR can be used to objectively score applicants on their skills, rather than relying entirely on their personal presentation skills and recommendations from people whom they choose to provide (Frost & Sullivan, 2004). Such objective measures may also be useful in avoiding discrimination charges when a job is awarded to one applicant over another.

"Now more than ever, innovative, efficient and effective training methods are needed, and surgical simulation holds great promise" (Brunner et al, 2005). MIST-VR can provide access to a wide variety of laparoscopic symptoms and procedures. This type of access in traditional education programs is being constrained by a number of financial, ethical, social, and logistical issues, many off which can be overcome through the addition of VR systems to the curriculum. Facilities that have adopted VR systems have found that they do increase student access to training opportunities, but they also allow the organization to explore new alternatives in training, evaluation, and experimentation.

Hypothesis 3: Reduced Training Time

Hypothesis 3: Virtual reality and game technology-based training environments can reduce the training time required to achieve proficiency in laparoscopic procedures.

As has been described earlier, current medical training focuses on mastering knowledge and contains few objective measures of technical skills. Research into the effectiveness of mannequins, simulators, box trainers, and virtual reality has identified a number of instances in which VR training can develop technical skills to a specified level within a specific amount of time. Without such objective measures, the traditional practice has been to take all students through the same curriculum at the same pace. At the conclusion of such a program, the degree of proficiency among students varies, but all are matriculated together. This situation compromises the mission of teaching hospitals by making it impossible to objectively determine when students are ready to progress to more challenging tasks or when they should receive more instruction (Cooke et al, 2006). Objective measurement would allow customization of training, extending training for those who are progressing slowly and accelerating training for those who learn more rapidly.

Adamsen et al (2005) demonstrated that both MIST-VR and GI-Mentor could separate experienced from inexperienced subjects based on their performance scores with the simulator. Gallagher et al (2004) took this a step further by using MIST-VR to identify a priori which students would have trouble mastering the psychomotor skills necessary for laparoscopic surgery. He went so far as to suggest that a simulator could determine which students would never achieve proficiency in laparoscopy and should be dropped from a training program. The ability to make such a decision early could potentially save a significant about of money and reduce future errors by unskilled surgeons.

Once the initial skill level of students is determined it is possible to separate them into groups that will be trained with different methods and at different paces. Since MIST-VR has been shown to measurably improve student performance, it is possible to use these measurements progressively to determine progress toward proficiency. Brunner et al (2005) has demonstrated specific training regimens that can be used to achieve proficiency given a specific beginning skill level. Aggarwal & Darzi (2006) and Brunner et al both present three different levels of proficiency that are achieved through mastery of a training program created by Mentice, the manufacturer of MIST-VR. Mastery of progressively difficult sets of tasks leads to higher levels of proficiency (Table 4 and Figure 11).

Table 4. MIST-VR training program for laparoscopic instrument proficiency

Task	Description
1	Grasp virtual sphere, place in wire-frame box
2	Transfer sphere between instruments, return to wire-frame box
3	Step instrument one and two alternately down a segmented cylinder
4	Grasp sphere, touch with second instrument, withdraw instrument, reinsert, touch sphere again
5	Grasp sphere, touch three orthogonal boxes sequentially with second instrument, use diathermy (third instrument) on each box
6	Combine tasks 4 and 5

Source: Jordan et al, 2000

In one study, students were required to perform Task 1 repetitively for 10 minutes while the system recorded performance in time and "economy of movement", a.k.a. minimal travel distance of the endoscopic effectors. Students demonstrated an average time with the right hand of 12.2 second with a standard deviation of 5.3 seconds. They demonstrated an average time with the left hand of 16.2 second with a standard deviation of 10.6 seconds. The fact that such tests can be measured and the results used to determine the duration of training is much more important than the raw results achieved during any one session. Note that "economy of movement" is not part of this hypothesis, but it is measured in centimeters of travel distance for the end of the instrument while performing the task. Shorter distances indicate manual proficiency of control and less potential trauma to the patient's body.

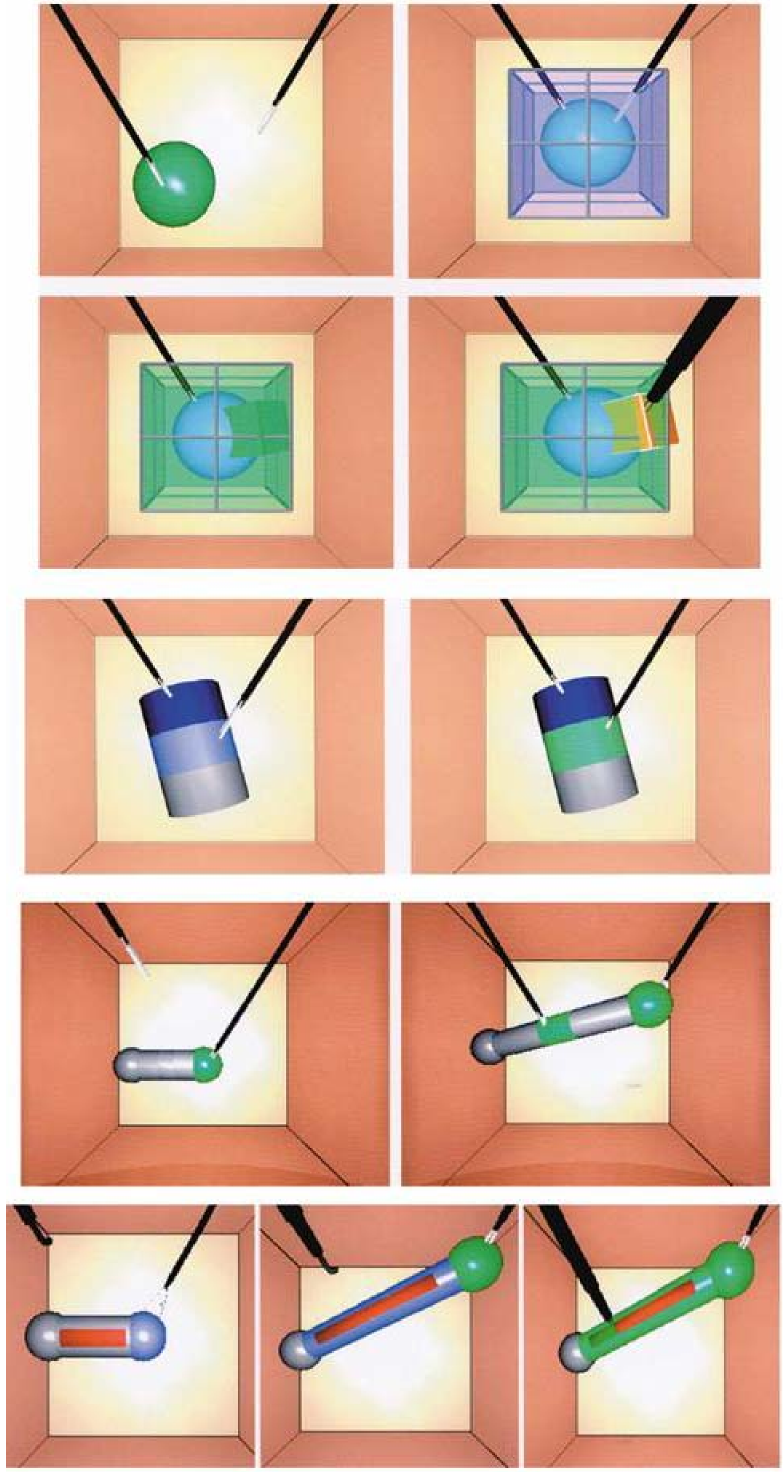

Figure 11. Exercises in MIST-VR skills course

Source: Gor, McCloy, Stone, & Smith (2003)

Grantcharov et al (2003a) have shown a learning curve through this training program to proficiency. His studies suggest that learning for Level 1 proficiency plateaus after two repetitions of the program. For Level 2, the plateau occurs after five repetitions. For Level 3 it is seven repetitions. These numbers provide a general framework of psychomotor training that can be expected to move an average student toward proficiency. Brunner et al (2004) executed a similar study in which he identified training plateaus on the way to proficiency. These plateaus are useful in predicting how much training a specific student will need to achieve proficiency based on his path through a training program. His study found that on average subjects could achieve proficiency after 7.1 hours of training. However, he emphasizes that neither a specific duration nor a specific number of repetitions should be used to assume proficiency for individual students. Performance should be measured for each student and the results of the experiments indicate where the average student will reach competence. Chaudhry et al (1999) has conducted similar studies and identified similar learning curves with plateaus of performance. He focused on the difference in the learning curve for early repetitions versus later repetitions, finding that surgeons improve their skills most rapidly in the first three repetitions of the training program.

Grantcharov et al (2004) have shown that students who learned their skills in a VR trainer are more rapid when performing live surgeries, and generate fewer errors. Enochsson et al (2004) and Seymour (2002) have extended this by demonstrating that students trained in VR are 29% faster at performing laparoscopic surgeries and make up to five times fewer mistakes. Seymour also demonstrated that non-VR trained students are nine times more likely to fail to make progress in their performance than those who use VR in their training.

Taken together, the evidence indicates that measurable progress toward proficiency can be made with MIST-VR. The medical schools can use these measurements to adjust training times to fit specific individuals. They may also go so far as to use VR system results to determine who to admit into their programs, selecting only those who show an aptitude for this unique form of surgery and who will be able to finish the programs efficiently.

The studies also indicate that VR systems can instill in residents a level of proficiency and confidence that allows them to perform real surgeries more rapidly. This aptitude can lead to reduced operating times for many years, reducing costs and increasing revenues driven by these students.

Hypothesis 4: Reduced Errors

Hypothesis 4: Virtual reality and game technology-based training can reduce the number of medical errors caused by residents and surgeons learning to perform laparoscopic procedures.

"There is no excuse for the surgeon to learn on the patient." William J. Mayo, 1927.

"The surgeon must indeed have learned from instruction or by his own inductions and observations, a great number of truths; but he must also have learned by practice a great number of aptitudes." Gilbert Ryle, *The Concept of Mind*, 1949. (both quoted in Murphy, 2007)

The number of errors committed by surgeons during operations has become a national issue. A 1999 study by the Institute of Medicine estimated that medical error is responsible for between 44,000 and 98,000 deaths per year (Institute of Medicine [IOM], 1999). One cause is the lack of medical standards across specialties, education programs, state certification boards, and individual experiences. Surgeons all learn different materials and different procedures. They also occasionally incorporate incorrect procedures into their skill set, have no means of identifying these as erroneous, and make no effort to acquire the correct procedures. As a result they will perform the incorrect maneuver or procedure over and over again throughout their career (R. Satava, personal communication, May 20, 2008). The national awareness of these types of problems is reflected in studies on the use of simulators and virtual reality in training. In most cases, the primary emphasis of the research studies collected for this dissertation was not on cost advantages, improvements in time, or improved access to symptoms, but was on the ability of a simulator to reduce the number of errors that occur on live patients.

MIST-VR has been the subject of many studies into its ability to reduce errors in laparoscopic procedures. The rapid increase in demand for laparoscopic surgery over the last ten years has created a demand for qualified surgeons that has exceeded the existing supply. Continuing Medical Education (CME) seminars lasting two to three days have been the dominant method by which practicing surgeons have gained their credentials in laparoscopy (Shalhav et al, 2002). At the same time Huang et al (2005) has shown that laparoscopic surgery has an error rate that is three times higher than that of open surgery. And, the error rate has not been going down over time as many had hoped as surgeons became more experienced at the procedures. Huang et al point to VR systems as one tool that can improve the performance of surgeons because they become familiar with the appearance of organs and tissue on a two dimensional computer monitor, the same type of visualization that is provided by laparoscopic operating equipment. Errors in identifying anatomy during an operation are a significant problem and may be improved through repeated practice in a VR environment. They also develop their proficiency with operating in three dimensions while observing their own actions in only two dimensions.

Martin et al (1998) and Resnik et al (1993) showed that the 100 year-old Halsteadian residency model in which the student learns in the operating room and assumes gradually more responsibilities is not working with more complex surgeries. For laparoscopic procedures in particular, observation does little to convey the skills that must be mastered. Only actual practice has been effective at this (Jordan et al, 2001; Gallagher et al, 2001b; Madan & Frantzides, 2007). For example, the fulcrum effect in which a surgeon's movements are reversed by the interaction of the laparoscopic instrument rods through the abdomen wall cannot be learned through observation. It can only be experienced in real surgeries or in a psychomotor-based simulator (Gallagher et al, 1999). Stefanidis et al (2006a) includes the limited haptic feedback and the loss of depth perception as additional factors that make laparoscopic training unique and difficult to learn by observation.

Murray et al (2005) calls for the integration of simulators into the teaching curriculum as an imperative to avoid adverse patient consequences due to error and inexperience. Korndorffer et al (2006) points out that the ACGME has not established a minimum number of laparoscopic cases that are necessary for a resident to graduate. But Park, Witze, & Donnelly (2002) and Rattner, Apelgren, & Eubanks (2001) have shown that residents currently have no exposure to advanced laparoscopy during their residency. Grantcharov et al (2003a) and Jordan (2000) have both studied the time to proficiency of surgeons practicing laparoscopy. The former showed that proficiency is not attained until between 10 and 30 procedures have been performed. The latter showed that most errors in surgery occur within the first 10 procedures. Both authors point out that making all of these errors on mannequins, in simulators, or with VR systems is far superior to subjecting patients to these effects (McNatt, 2001). Given decades of experimentation and improvement, VR-based systems have been shown to be effective at teaching laparoscopic skills and moving the learning curve off of live patients and onto virtual patients. Not to use these systems when they are available and effective could be considered negligent.

Aggarwal et al (2006), Brunner (2005), and Maithel (2006) have each shown that MIST-VR does measure errors in hand movement when performing prescribed procedures. When performed inside of a live patient these errors can cause discomfort or damage which is totally avoidable if the resident or surgeon can be trained with a device like MIST-VR. Grantcharov et al (2004) similarly demonstrated that MIST-VR could effectively reduce error movement through practice.

Not all authors are positively impressed with VR trainers like MIST-VR. Madan & Frantzides (2007) introduced MIST-VR into a curriculum where they were already using box trainers. Their experience showed that there was no difference between those trained with either of the devices. Kothari et al (2002) also demonstrated that the improvements in specific skills using MIST-VR are equivalent to the improvements achieved through the five day Yale Skills Course. These are very positive findings in that they indicate that a VR system may be equally as effective as a much more widely accepted form of training, a faculty led observation course and a box trainer. If each method can deliver equal results, then the issue is no longer one of effectiveness in raising skills or reducing errors, but instead shifts to cost and access issues. As shown earlier many authors including Scott et al (2000) consider the cost and limited access of cadavers, animals, and biological tissue to be a significant factor limiting medical training. When VR-based systems are shown to be equal in effectiveness, they simultaneously offer solutions to these problems.

Chadhury et al (1999) showed that students using box trainers have the opportunity to practice procedures, but that the device has no means of measuring the effectiveness of their performance. A faculty member must be present to observe and evaluate the procedure if it is to be scored. The availability of these faculty members is one of the most limiting factor in medical education (R. Satava, personal communication, March 17, 2008).

Enochsson et al (2004) conducted experiments in which his team demonstrated that students who were trained with MIST-VR were five times less likely to make a mistake than students trained without the device. Coincidentally, Seymour et al (2002) also found that students who trained with MIST-VR were five time less likely to injury the gallbladder or to burn non-target tissue during surgery. Seen another way, students who do not use VR training are five times more likely to make mistakes than those who are trained with it. Compare that to the earlier statistic that laparoscopic surgeons are three times more likely to make mistakes than are open surgeons. VR presents an opportunity to significantly reduce errors in a very complicated and error-prone family of procedures.

Gallagher et al (2001b) and Cuscheri (1995) documented a condition they called “surgical fatigue syndrome.” It is characterized by mental exhaustion, increased irritability, impaired surgical judgment, and reduced dexterity – all brought on by the exertion required to perform intense, hours-long surgeries. Surgeons usually do not repeat these operations daily and have little opportunity to develop a “surgical stamina” to deal with them effectively. They suggest that simulators and VR devices are a perfect environment in which to develop and maintain this type of stamina. Just as athletes use various out-of-game workouts to build their abilities, surgeons need a workout regimen and facility to achieve similar conditioning. Repeated practice on cadavers, animals, or live patients is impractical or impossible – leaving just the training tools we have described earlier. Of all of these, VR may present the lowest recurring costs and be the most amenable to customization for specific skills.

Gallagher et al (2001a) was also successful at raising the mean performance of students to a level equivalent to that of experienced surgeons. This took only three repetition of a training program. However, the group of students had a much larger standard deviation in their scores. This indicates that though some students are very talented at reaching expert levels, an equal number have difficulty progressing quickly by any means of training.

Ali et al (2002) conducted a study to determine whether increasingly difficult exercises with MIST-VR measurably improved the performance of students and whether such improvement might transfer to better skill levels at the completion of a program. He achieved positive results on both counts, showing that more difficult exercises did indeed lead to better real performance. This seems to align simulators with exercise as a means of improving performance.

Schijven et al (2005a) has demonstrated that the VR training course at Eindhoven Hospital measurably improves surgical skills that are later exhibited in an operating room environment. In fact, it improves skills more than the use of the lectures and video presentations that have customarily been part of the training program.

Grantcharov et al (2001) showed that performance in MIST-VR correlated very closely with student performance on animal models. He concluded that the system would be a promising method for objectively assessing psychomotor skills. Torkington, Smith, Rees, & Darzi (2001a; 2001b) came to a similar conclusion after a three week skills test using the system.

The numerous researchers cited in this section have demonstrated that students who train with the MIST-VR system do improve their performance and reduce the number of errors that they make. There is ample evidence that VR-based systems can reduce errors that would otherwise occur on live patients.

Results

The questions regarding cost, access, time, and errors surrounding the use of virtual reality in general and MIST-VR in particular for laparoscopic education are more widely applicable to the use of new technologies in medical education. This study focused on one application for which abundant scientific studies had been done. But there is a crisis unfolding in medical education that must be faced and addressed in coming years. Members of society have raised their expectations of the medical profession, but the standards and methods for preparing physicians and surgeons have changed very little.

Some would point to the Flexner report of 1910 and the establishment of the residency methods by Halstead as the last major changes in medical education. Richard Satava (personal communication, February 22, 2008) believes that the medical profession goes through a major change only once per century and that the next one is happening right now. Satava believes that virtual reality is currently the most promising technology for improving medical education (personal communication, February 22, 2008). Given the rapid advances in computing and communication that have emerged in recent years, and their adoption by most industries, it should not be surprising that these are considered some of the most promising improvements in medical education.

H1 Lower Cost: Supported

Researchers have expressed their opinion that the cost of training with non-human and non-animal devices is significantly lower than many of the older methods. Frost & Sullivan (2004) and Bridges & Diamond (1999) provide some of the most quantified data on cost savings associated with simulators and VR. In this dissertation I have identified a number of cost items that can be reduced through the use of virtual reality. Many of these have been quantified to demonstrate the extreme magnitude of differences between surgical practice on human cadavers, porcine models, simulators, and virtual reality. There are also a number of indirect savings that accrue from a reduction in medical errors and increased access to training. It is clear that significant cost savings can be accrued through the use of virtual reality and that the opportunity to expand its use will probably continue to grow as the technologies improve.

H2 Better Access: Supported

The evidence does strongly support the position that access to patients and specific symptoms by residents for the purposes of medical education is a significant problem and that the situation can be improved through the use of simulators and virtual reality. Medical residencies typically last for four years and combine time in didactic, observational, and hands-on learning. During this period, every student must encounter multiple opportunities to observe every symptom and practice every procedure that will be used once they become surgeons. The likelihood of achieving this for every student at every institution and with sufficient repetition and oversight is vanishingly small. Researchers and educators admit that the number of symptoms and medical procedures that a student must master is increasing rapidly and far exceeds what can be covered in a Halsteadian residency.

Simulators and virtual reality provide synthetic and purposefully constructed scenarios that can deliver exposure to specific symptoms. This can be accomplished repetitively and performance can be measured by these computerized systems. The advantage of virtual reality and game-based technologies is that they present situations via software and computer hardware that is largely generic. These software worlds can be reconfigured, reset, and reused much more easily than physical devices like mannequins and simulators. There is a great deal of support for the hypothesis that game-based systems can provide much better access to patient symptoms than can other forms of training.

During the course of this study we also uncovered a related issue. One of the most limiting factors in providing medical education is access to sufficient expert faculty members who can teach the residents. Any form of training that can teach without requiring the presence of a faculty member can be a valuable addition to the educational process (Dunkin et al, 2007).

H3 Reduced Training Time: Supported.

This research revealed two different types of “time reduction” that occur with the insertion of VR into the training curriculum. My initial hypothesis was that students could become proficient more quickly with the use of VR than without its use. There are a large number of studies that demonstrate that students do indeed reach proficiency in a shorter amount of time when using VR than when learning only via more traditional methods. Part of this improvement is due to the fact that computer-based teaching systems have the ability to measure the performance of the resident. With such measurements it is much easier to determine when a particular student is ready to move on to more difficult material and when he or she has achieved proficiency.

Prior to the use of these systems, proficiency was assumed for an entire group that had spent the specified amount of time in a teaching program. Upon reaching this duration-based threshold all of the students were matriculated to the next level. Some students would be released too soon. Others would have been held back because they reached proficiency sooner, but there was no mechanism for objectively measuring this. A virtual reality system can use the computer to stop training when the student has measurably achieved proficiency. Some studies have also shown that simulators can be used to determine a priori which students would never reach proficiency in laparoscopy. This would allow them to be moved into a different specialty rather than continuing through a program toward a specialty for which they are not suited.

The second, and surprising time factor, was that students trained with VR had a much better understanding of the laparoscopic surgeries they were performing. Their knowledge, confidence, psychomotor skills were so improved that researcher found that they performed real surgeries faster than their more traditionally trained counterparts. I did not suspect that VR could create better skills to a degree that it would reduce the time that the surgeon, medical staff, and patient spend in the operating theater. This can lead to reduced costs for many years into the professional career of the surgeon. The hypothesis on reducing time in training due to the use of virtual reality and game technologies was supported by the research literature.

H4 Reduced Errors: Supported

The fourth hypothesis proposed that the number of errors committed by surgeons on patients could be reduced through training with VR devices. This proved to be one of the most active areas of the research literature. The interest of medical professionals is much more on their ability to help the patient and to avoid injury than it is on cost and duration. VR was able to develop skills with procedures and equipment that transferred directly into a reduction of the number of errors made during live surgeries. VR also provides a training environment in which early mistakes with procedures can be worked out and eliminated before a surgeon is allowed to practice on a live human. Researchers have shown that a surgeon or resident must perform a procedure at least ten times to get beyond the period in which most errors occur. VR systems provide an environment in which this can be done without injury to a real patient. The evidence strongly supports the hypothesis that virtual reality systems can reduce the number of medical errors that occur on live patients.

Model of Medical Education: Supported

I proposed a model of medical education which showed virtual reality including game technologies as the next major addition to or transformation of the medical education curriculum. The evidence collected in this study indicates that VR systems are becoming much more accepted in medical education and that the technical limitations that existed when early versions of devices like MIST-VR were first introduced in the mid 1990's are already being overcome. When asked if any other technology can offer better improvements in medical education than virtual reality, Dr. Richard Satava one of the pioneers in this area, responded that he believed that VR was the next major change in medical education and that he was not aware of another technology that held equal promise for improving the current situation (R. Satava, personal communication, February 16, 2008).

The earlier adoption of mannequins and simulators in medical training indicates that human symptoms can be sufficiently replicated by man-made devices to provide valuable training to surgeons. VR is not an entirely new technology in medicine. It is a software-based version of mannequins and simulators. Technical limitations have made it difficult to reproduce the behaviors of the human body in software in the past. But the advances in computer software and hardware that are being driven by computer games for entertainment are overcoming these limitations.

Companies are spending billions of dollars to create more realistic entertainment and these investments can be leveraged by many other industries, to include medical education. VR as its own research area declined many years ago. These technologies are now part of the gaming agenda, but the term “virtual reality” is a necessary alternative for many industries. Medical education is adopting VR or game technologies just as they adopted box trainers, mannequins, and simulators in the past.

Misleading Domain Assumptions

Within the medical education community and in the published papers that were collected for this study, there exist a number of assumptions about both established and emerging forms of training. In many cases these assumptions demand a higher degree of proof of effectiveness from emerging ideas, while accepting established practices with much less support. Misleading assumptions that are embedded in the material that was studied are explored below.

Assumption 1: Didactic Education is Effective

The basis of most educational programs is didactic lecture accompanied by evaluation tools like tests. Though this has been a core method for centuries, there are a number of studies in all fields that demonstrate that it is a very poor method of conveying information to a student. In the medical profession there have been numerous studies which have shown that didactic methods have little or no impact on the behavior of surgeons and that problem-based learning, to include the use of simulators, is a much more effective form of learning (Boshuizen & Schmidt, 1995; Norman & Schmidt, 1992; Patel & Kaufman, 1995; Bennett, 1994). Though surgeons or residents may learn new information during educational lectures, they do not incorporate it into their practice. It has no impact on their actions in delivering medicine (Davis, Thompson, Oxman, & Haynes, 1995; Davis et al, 1999; Weller, Dowell, Kljakovic, & Robinson, 2005).

Contrary to this trend, mannequins, box trainers, simulators, and virtual reality allow students to practice psychomotor skills during their training. This approach to education has been shown to be much more effective in creating skills that are actually applied during practice (Binstadt et al, 2007). In particular, established physicians are much more likely to change their behaviors due to hands-on practice during education than they are following didactic delivery of the same information.

Assumption 2: Cost of Systems is Not an Issue

As pointed out in exploring Hypothesis 1, the studies on medical VR are conducted entirely by surgeons and researchers. They do not include participation by the financial controllers who can provide real numbers for the fixed and variable costs associated with different forms of training. This is positive in that it allows scientific measurement of the effectiveness of these devices. But it is negative in that it assumes that the health care system can afford to deliver education and treatment by any means, regardless of the cost.

Pressures to control medical costs, especially in the face of the increasing number of patients paid through the Medicare and Medicaid systems, will have an impact on the money available for medical education in the future. It is important that the medical education system begin to identify the most cost effective methods of preparing residents for practice, whether that includes or excludes the use of simulators and virtual reality.

This survey of the literature on the use of simulators and virtual reality in medical education revealed only one research paper which analyzed the financial impact of using these devices (Bridges & Diamond, 1999) and one industry study on the topic (Frost & Sullivan, 2004). Several papers cited the amount of money they had spent in acquiring a system, but provided no analysis on the cost/benefit of that investment (Hamilton, 2001; Hyltander, 2003; McClusky et al, 2005; McNatt & Smith, 2001).

Assumption 3: Sufficient Access to Faculty and Patients is Possible

Several studies have shown that the apprenticeship model of teaching skills is just as good as, and in some cases better than, simulators and virtual reality in teaching new skills. However, each of these studies assumed that the traditional methods of education could provide students with sufficient access to both faculty members and to patient symptoms to train all of the skills necessary (Gerson & Van Dam, 2003). Such access was certainly present for the purposes of the study. But the limited numbers of qualified medical faculty members is a major issue in health care today (Dunkin et al, 2007; R. Satava, personal communication, March 17, 2008). It appears that the current system cannot meet the demand for new physicians and surgeons that is emerging and one of the major limitations on this is the number of available faculty members.

The assumption that patients will present the necessary symptoms for assessment and treatment while the resident is available is significant. Medical practice has become much more complicated and extensive than when the Halsteadian apprenticeship model was established 100 year ago. Cooke et al (2001) used the term “hypertrophied” to describe the rapid expansion in medical knowledge that must be mastered. Many of the skills needed are also part of rare but critical events which most residents will never have an opportunity to witness. Like other lifesaving and life protecting professions, medical education must be able to create these important symptoms repeatedly and on demand to insure that surgeons are prepared to respond to them, something that simulators and virtual reality can be specifically designed to do.

Assumption 4: Practicing on Live Patients is Acceptable

Finally, for centuries, surgeons have had to practice their craft on both cadavers and living human patients. In many cases there simply was no alternative to working on a real case with a real patient. This has led to the deeply embedded belief within the medical profession that this practice is acceptable for the good of society. However, a very strong movement in patients' rights is now limiting the ability of residents to conduct learning and to make mistakes on living patients. Many practices that led to better skills in surgeons also led to poorer health in the patient. This is much less acceptable than it has ever been in the past. Medical schools, faculty, and residents are finding new restrictions on the type and amount of training that can be conducted with a live patient. It appears that these pressures will only increase and require a significant reassessment of the practices in a teaching hospital (Murphy et al, 2007; Murray et al, 2005; Satava, 2004a; Ziv et al, 2005).

Some countries are also including the use of live animals in these restrictions. The United Kingdom has banned the use of live animals as surgical subjects for teaching since 1926 and other countries in Europe are moving in a similar direction (M. Kitching, personal communication, June 12, 2008; Waseda, 2005; Moorthy, 2006). So all living subjects may soon be off limits as platforms for teaching medical residents, and a nonliving alternative will be necessary

Discussion

All professions, practices, societies, and individuals evolve and change over time. Hopefully, they progress and improve so that they can contribute more to society, family, and individuals than they did in the past. In spite of these forward movements there is always resistance to change. Once a system of activities is working, there is a fear that changes to this system will lead to a loss of productivity or the loss of stature for those who built it. Change in an open society cannot be stopped, though in many closed societies it can be slowed to a crawl.

Thomas Kuhn (1970) famously described the real progression of science through the ages as a series of revolutions. Rather than occurring as smooth transitions from one idea to the next (evolution), scientific progress occurs through the dramatic overthrow of established ideas that contain errors (revolution). The history books usually present a peaceful, logical, and progressive picture of change. But Kuhn showed that the true story involves the suppression of new ideas by the established high priests of any scientific field. These people hold a mental mindset that was built around prior assumptions and beliefs about the universe and new ideas typically do not fit into this picture. New ideas require deconstructing what leaders have believed to be true, and a subsequent reconstruction of ideas in accordance with new evidence that is available.

The established leaders in a field have built their positions on the established theories. If these theories are displaced by new ideas, then potentially their positions of leadership must be relinquished to the next generation of thinkers as well. This creates a personal motive to resist these changes and to prevent them from displacing the existing body of beliefs.

Kuhn showed that the only way new ideas can displace old ideas is through a revolution. The new ideas and the people who support them are suppressed and ignored by the existing establishment. These new ideas must gather strength surreptitiously through discoveries of cases that cannot be explained by the old model, but which do fit within the new model. At some point, major unsolved problems in fields like physics, chemistry, mechanics, and biology are solved through the new methods and new ideas. As this occurs it becomes impossible for the existing status quo to remain. These revolutions build beneath the surface and erupt to overthrow established doctrine.

Medical education appears to be going through a “once in a century” change to its dogma and methodology (R. Satava, personal communication, February 22, 2008; Martin et al, 1998; Reznick,1993). Simulators, virtual reality, and technologies from the computer entertainment industry are some of the forces that are on the verge of transforming this field. The pattern of resistance to new techniques and objections to their validity sounds very similar to Kuhn’s description of the scientific revolutions of centuries past.

Conclusion

This thesis has explored the impact that virtual reality and computer game technologies are having on medical education and the potential future results of this impact. From a business management perspective this is an instance of Schumpeter’s creative destruction or Christensen’s disruptive innovation. A new technology is enabling a new set of beliefs and practices in a very large business area. The 1997 U.S. census showed that health care costs were over $418 billion (US Census, 2001). Carey (2006) reported that annual health care costs in the United States are currently $2 trillion. Kaufman & Stein (2006) reported that health care represents 16% of the U.S. gross domestic product. Medical education in schools, hospitals, and as CME is a significant and valuable fraction of this annual business. As VR enters this field, established education providers and their products may be displaced and their business’ existence threatened. Improvements realized through the use of VR could result in reductions in:

- Faculty positions,
- Cadaver usage,
- Animal models,
- Organ box trainers, and the
- Materials and facilities that support these.

As Schumpeter and David Wells both pointed out, inefficiencies accrue in a static system (Perelman, 1995). Changes like new technologies make it possible to improve efficiency by transforming the way a business service or product is delivered. But, in the process those who are dependent on the old business find their livelihood threatened or even eliminated.

Medical practitioners or students who are planning to take advantage of the demand for faculty at teaching institutions may find that the demand is mitigated by the presence of computer-based training systems that can be operated by the students without faculty intervention. These systems may also be able to evaluate and score aspects of student proficiency that were previously handled by research assistants or faculty members.

Companies that provide high quality animal models as surrogates for the human body may find demand for their products waning. These animals are of a higher quality with more narrow specifications than are needed in other industries. They cannot be sold as food products and still maintain the revenue levels necessary to sustain the business in its current form. Animal providers may be forced to resize to a smaller customer base, move downstream into the food products area where competition is tighter, or find an entirely new base of customers for their products. This latter might be in scientific experimentation outside of the medical field.

The manufacturers of box trainers may find that there is less demand for the boxes that are used as a casing for human, animal, or synthetic organs in education. These companies may find new business in outfitting VR systems with tactile interfaces which support the visual interfaces of the systems. The “box” may need to be upgraded to a full body mannequin or a more accurate replica of a specific portion of the body used for a part task trainer. They may find that their knowledge of how to reproduce the feel of a real body is a valuable skill to those who must program this feel into a VR model in the future.

Logistics chains that previously delivered cadavers, pigs, and cats to medical schools may need to redirect their business toward the handling of sensitive medical training simulators and storage that is conducive to electronics rather than biological products. Facilities that were used for operating on pigs may need to be modified to accommodate simulators, with a larger focus on delivering electricity than delivering anesthesia or carrying away body fluids.

All of these are potential business impacts driven by the adoption of virtual reality and changes in traditional methods of training. This study examined only the MIST-VR laparoscopic surgical training device in detail and incorporated several studies from other surgical specialties. But the sea change that is suggested here may emerge in a similar form all through the business landscape of medical education. An understanding of these potential changes is an important contribution to the business management literature.

Chapter 5: Recommendations for Future Work

This thesis has provided some very compelling evidence for improvements that are possible in cost savings, providing access to representative patient symptoms, improving training times, and reducing error rates in laparoscopic surgery. Future studies within the medical education and hospital administration field should be pursued which are able to provide concrete cost data on the differences between current forms of training – didactic lecture, human cadavers, live patients, live animals, and box trainers – as compared to newer systems like simulators and virtual reality. Such a study is necessary to provide quantitative data on cost advantages. The return on investment for different types of VR systems should be established and made available to organizations that must make financial decisions on whether to adopt new tools and techniques. Such a study needs to go beyond the initial acquisition cost of the materials, devices, and systems. It should include the operating, maintenance, and disposal costs of all of the alternatives.

Another area of interest is in comparing access to patients, symptoms, and faculty via the traditional resident observation, lecture, and the gradual assumption of medical responsibility – a.k.a. the Halsteanian model – with a newer system that relies on computer-based devices like simulators and virtual reality. Several published studies assume that live access to patients and symptoms by a resident and an available faculty member is sufficient for teaching all knowledge that is required. Given the increasing limitations on faculty time and the legal and ethical limitations on operating on live patients, an understanding of the degree to which a resident can be led through the traditional teaching model is necessary. This limited access scenario for traditional teaching would provide a more realistic comparison to methods that incorporate simulators and virtual reality.

Both of these studies must be done from within a teaching hospital. They require access to information that does not reside in the public domain and that may not have been collected in previous studies. The latter topic may require a longitudinal study involving multiple medical schools that are using different combinations of teaching methods.

The increasingly open attitude of society in general and the members of society who pursue a medical profession in particular, will likely erode the psychological and social barriers that keep new technologies out of medical education. At the same time, technological advancement will create the hardware and software tools necessary to accurately and valuably model the human body and surgical interactions with it. The changes in both of these areas will lead to the opportunity to use virtual reality and game technology-based tools in medical education. It is important that the profession objectively understand what can and cannot be accomplished with such tools so that they can be applied effectively. This study has attempted to extract the state of these technologies for teaching laparoscopic surgery, but the potential goes far beyond this and needs to be investigated to take full advantage of the technologies.

Appendix 1. Medical VR Reference Coding Matrix

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Hypothesis 1: Training in laparoscopic surgery can be accomplished for significantly lower costs																	
AHRQ	2000	X								X				X			Estimated cost associated with deaths from medical errors of all types is $37.6 billion annually
Aggarwal	2007	X		X		X				X	X						VR training shortens the learning curve, reducing both cost and time in education.
Bridges	1999	X								X							Learning in the OR is much more expensive than learning in VR
Brunner	2005	X	X	X	X	X	X			X	X						Students need new forms of training to achieve proficiency under current regulations on work hours.
Cohen	1999	X								X				X			Medical error in all fields results in between 44,000 and 98,000 people dying as a result each year
Derossis	1998	X				X				X							Collecting metrics in live surgery is difficult, using VR sims is less expensive
Eastridge	2003	X				X	X				X						Regulations limiting resident work hours leads to a need for a simulator to hone skills.
Frost	2004	X		X	X					X	X						Research study creates and applies model of cost/benefits of Immersion Medical's AccuTouch laparoscopic simulator.
Grantcharov	2003	X	X	X	X	X	X			X	X						It takes 10-30 operations for a laparoscopic surgeon to master skills.

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
Hamilton	2001	X								X	X						Wet tissues and sutures are an avoided cost when training with VR rather than humans or animals.
Korndorffer	2006	X	X		X	X	X			X	X						88% consider VR skills labs effective at improving OR performance. But only 55% have such labs.
Madan	2003	X		X		X	X			X	X	X					Game skills improve laparoscopic skills (inferring 3D from 2D data). MIST-VR does not have haptic feedback.
Madan	2005	X	X			X	X			X	X	X					Students prefer LTS2000 over MIST-VR. Simulations reduce training costs. Table 3 has directly applicable data on MIST-VR.
McClusky	2005	X	X			X	X			X	X					X	ACGME regulations limit hospital time, but sims at home may be allowable. Immersion Medical has developed and markets ProSim-J for this purpose.
McNatt	2001	X			X	X	X			X	X						MIST-VR training leads to faster operating times and fewer errors. Operating time is correlated with cost of facilities and personnel. Errors are correlated with lawsuits.
Pearson	2002	X	X		X	X	X			X	X	X					MIST-VR and Box trainers are both good for teaching knot tying skills. (Quotable paragraph.)
Rosenberg	2005	X								X		X					Video game aptitude can predict proficiency in laparoscopy. But using games does not improve laparoscopic skills.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Rosser	2007	X			X					X	X	X			X		Historical medical error data in this study. Video game skills correlate with laparoscopic skills
Scott	2000	X			X	X				X	X						raining devices provide better training at a lower cost that learning in an operating room with live procedures
Summary:		(Brunner, 2005) Operating room time is very expensive and not an effective way to train residents. It can be a key limiting factor. MIST-VR eliminates need for faculty hand-holding. (Eastridge, 2003) MIST-VR provides realism at a lower price. (Grantcharov, 2003) Practicing on the first 10-30 patients is a very expensive approach to training residents. Better to get these practices into a simulator. (Korndorffer, 2006) Lap trainers reduce costs, skills labs provide good training, but few hospitals have these. Is it a cost question? (Madan, 2003)VR reduces training time, which reduces cost. Collecting metrics in manual training is very expensive compared to using computerized VR. (McClusky, 2005) VR does not require recurring materials costs (animal parts). (McNatt, 2001) VR obviates the need for animal models in early experiences. (Pearson, 2002) Predict VR for certification by 2010. (Rosenberg, 2005) Believes in games as low-cost and readily available skills trainers. (Rosser, 200&) Medical errors cost $37.6B/year, VR can reduce this cost. (Frost, 2004) AccuTouch pays for itself within 169 days of purchase through reduced costs in OR, equipment, and faculty time.															
Analysis:		Only Frost & Sullivan collected real cost data. Most others inferred cost savings after proving effectiveness of VR. Grantcharov's study provides a solid link to cost savings by eliminating live training for a surgeon's first 10-30 procedures. When tied to the costs cited by Rosser this creates some motivation for finding any alternative to the current process of training.															
Hypothesis 2: Game-based training environments provide better access to patient symptoms.																	
Aggarwal	2006		X	X	X	X	X										MIST-VR can measurably improve student performance.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Ali	2002		X		X	X	X			X							VR provides measurable improvement in high school honors students who are used in laparoscopic experiments.
Brunner	2005	X	X	X	X	X	X			X	X						Students need new forms of training to achieve proficiency under current regulations on work hours.
Cooke	2006		X	X									X	X			Medical procedures and education have become extremely more complex since 1910. Requires new methods of training and practice. Public also has higher expectations of surgeons.
DeMaria	2005		X			X	X			X	X						Night-call does not impair learning of laparoscopic skills. This study demonstrates the usefulness of VR systems in creating tools for other studies.
Flexner	1910													X	X		Report on the state of medical schools in 1910
Grantcharov	2003	X	X	X	X	X	X			X	X						It takes 10-30 operations for a lap surgeon to master skills.
Grantcharov	2004		X	X	X	X	X			X	X						Training with MIST-VR allows students to perform surgery faster and with fewer errors.
Jordan	2001		X	X	X	X	X			X	X						Compares MIST-VR, Box trainer, and nothing. MIST-VR is best.
Korndorffer	2006	X	X		X	X	X			X	X						88% consider VR skills labs effective at improving OR performance. But only 55% have such labs.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Kotharl	2002		X		X	X	X			X	X						MIST-VR is equivalent to the Yale Skills Course (5-day training).
Lane	2001		X			X	X	X	X		X	X		X	X		Survey of medical education devices and believe that current medical education methods do not provide sufficient opportunity to practice critical skills.
Madan	2005	X	X			X	X			X	X	X					Students prefer LTS2000 over MIST-VR. Simulations reduce training costs. Use Table 3 and related data
Madan	2007		X	X	X	X	X			X	X			X			No difference between Box and VR training.
Maithel	2006		X	X	X	X	X			X	X						VR holds great promise, but "current" (older) interface limits evaluation.
MacFayden	1998																For cholecystectomy believe that this number is between ten and thirty surgeries.
McClusky	2005	X	X			X	X			X	X					X	ACGME regulations limit hospital time, but sims at home may be allowable. Immersion Medical has created the ProSim-J specifically for this purpose.
Pearson	2002	X	X		X	X	X			X	X	X					Quotable paragraph. MIST-VR and Box trainers both are good for teaching knot tying skills.
Pham	2005		X			X	X			X	X						RF/ST is less frustrating to students than MIST-VR.
Reznik	1993		X														Simulation is enabling a major shift in medical training. These shifts occur very infrequently.

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
Schijven	2005		X		X	X	X			X	X						MIST-VR and LapChol systems improve lap skills more than lecture and observation of procedures.
Summary:		(Brunner, 2003) Legal restrictions on resident work hours are a significant limitation on their access to patient symptoms. VR/sims can improve this access. (Grantcharov, 2003) It takes 10-30 surgeries to become proficient in a procedure. Accessing live patients can be very difficult to reach this level. Computer-based simulators provide standardization, objectivity, and metrics. (Korndorffer, 2006) Practicing physicians learn lap surgery from a weekend seminar and have little other access to patients and real symptoms. (Madan, 2005) Students find VR training interesting enough to keep their attention on it. (McClusky, 2005) Sims may allow students to train at home, as with the ProSim-J. (Pearson, 2002) Lists 6 benefits of VR training superiority. (Aggarwal, 2006) Lap skills must be mastered before entering the OR, not once in the OR. (Grantcharov, 2003b) MIST-VR provides repeated practice, standardized tasks, and unbiased measurement. (Kotharl, 2002) VR is equivalent to a 5-day skills course. (Madan, 2007) MIST-VR is equivalent to a Box trainer. (Maithel, 2006) Allows objective scoring on tasks. (Pham 2005) Negative student opinion of MIST-VR. (Schijven, 2005) MIST-VR provides better training that lecture, videotape, and observation. (DeMaria, 2005) MIST-VR device is accessible as a tool for conducting other studies. (Jordan, 2001) MIST-VR is better than a box trainer.															
Analysis:		Students have to get 10-30 procedures under their belts before working on humans. How can they do this except simulation? MIST-VR has been shown repeatedly to be an effective trainer. It provides objective measurement of performance which is very difficult and expensive to achieve in real surgery.															
Hypothesis 3: Game-based training environments reduce the time required to achieve proficiency.																	
Adamsen	2004			X		X	X			X	X						MIST-VR and GI Mentor can identify experienced and inexperienced subjects. So they are valuable tools in determining skills achieved for certification
Aggarwal	2006		X	X	X	X	X										MIST-VR can measurably improve student performance.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Aggarwal	2007	X		X		X				X	X						VR training shortens the learning curve, reducing both cost and time in education.
Korndorffer	2005			X		X				X							Video-based training in suture tying leads to more rapid performance in real surgeries.
Brunner	2005	X	X	X	X	X	X			X	X						Students need new forms of training to achieve proficiency under current regulations on working hours.
Brunner	2004			X		X	X			X	X						Identifies the amount of training with MIST-VR that is necessary to reach proficiency.
Chaudhry	1999			X	X	X	X				X	X			X		Determines proficiency based on error rates and time taken to complete tasks.
Cooke	2006		X	X									X	X			The educational mission of teaching hospitals is compromised by the absence of performance standards and assessment methods that can clearly establish that learners are ready to advance to the next level of independence and challenge.
Enochson	2004			X	X	X	X			X	X	X					Experience with computer games improves simulator performance, which in turn improves surgical performance.
Frost	2004	X		X	X					X	X						Research into cost/benefits of Immersion Medical's AccuTouch laparoscopic simulator.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Gallagher	2001			X	X	X	X			X	X						Laparoscopic surgeries can be long and test the stamina of the surgeon. MIST-VR can be used to develop stamina prior to real surgery. Like a workout for medical skills.
Gallagher	2004			X	X	X	X			X	X						MIST-VR can distinguish between experts and novices. It can also identify those who will have trouble developing the necessary psychomotor skills and may never be able to achieve laparoscopic proficiency.
Grantcharov	2003	X	X	X	X	X	X			X	X						It takes 10-30 operations for a lap surgeon to master skills.
Grantcharov	2003		X	X	X	X	X			X	X						Training with MIST-VR allows students to perform surgery faster and with fewer errors.
Grantcharov	2003			X		X	X			X	X	X					Users of computer games learn laparoscopic skills faster than non-gamers.
Huang	2005			X	X	X	X			X	X	X					Laparoscopic surgery has three times more errors than open surgery. This is not decreasing with time. Game technologies like 3D visual engines can improve identification of internal anatomy. Very good argument for games, Very good support for reducing error rates.
Jordan	2001		X	X	X	X	X			X	X						Compares MIST-VR, Box trainer, and nothing. MIST-VR is best.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Jordan	2000			X	X	X	X			X	X	X					VR training leads to faster training, better instrument manipulation, and better visual identification. Most errors occur in first 10 operations.
Madan	2007		X	X	X	X	X			X	X			X			No difference between Box and VR training.
Madan	2003	X		X		X	X			X	X	X					Game skills improve laparoscopic skills (inferring 3D space from 2D visual data). MIST-VR does not have haptic feedback.
Madan	2005			X	X	X	X			X	X						MIST-VR comparisons with porcine training. Each skill acquired within 10 minutes on the simulator.
Maithel	2006		X	X	X	X	X			X	X						VR holds great promise, but "current" (older) interface limits evaluation.
Reilly	2008			X	X	X				X		X					Playing games improves laparoscopic performance.
Seymour	2002			X	X	X	X			X	X	X					VR training increases speed and reduces errors in gall bladder surgery.
Shalhav	2002			X	X									X	X		The rapid popularity of laparoscopic surgery created a shortage of trained doctors. Most practicing surgeons learned laparoscopy at a weekend seminar to meet the demand.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Stefanidis	2006			X	X	X				X							Laparoscopic surgical procedures contain a number of limitations that require practice to master. The "fulcrum effect" in which a surgeon's movements are reversed by the orientations of instruments through the abdominal wall is a commonly cited example.
Summary:	(Brunner, 2003) Regulations require a new form of training. VR is the leading option available. (Grantcharov, 2003) Students trained with MIST-VR achieve proficiency faster and make fewer errors in real surgery. (Madan, 2003) Game skills are positively correlated with laparoscopic skills. (Frost, 2004) AccuTouch can get students to proficiency for surgery faster. (Adamsen, 2004) VR systems can identify who is experienced, can be used as tool for certification and end of training program. (Brunner, 2004) MIST-VR can lead to a measurable proficiency. (Chaudhry, 1999) Measurable error rates indicate proficiency objectively. (Gallaher, 2001) Laparoscopic surgery requires stamina, which can be developed through repeated use of simulators. (Huang, 2005) Laparoscopic surgery has high error rates and these were not decreasing over time. Need a new means of improving skill, especially in identifying internal anatomy. VR allows visualization and repetition. (Jordan, 2000) VR leads to faster proficiency, better visual identification. (Madan, 205) Shows that a skill can be learned in 10 minutes in either VR or porcine training. (Stefanidis, 2006) Laparoscopic surgery requires repetition to master skills. (Seymour, 2002) VR leads to faster skill development. (Shalhav, 2002) Explosive popularity of laparoscopic surgery led to a crisis of skilled surgeons. How to provide large volume proficiency?																
Analysis:	There are two keys in reducing time to proficiency: (1) The proven effectiveness of the VR sim. MIST-VR has achieved this. (2) The ability to measure proficiency during performance. MIST-VR and other computerized systems allow this. Previously proficiency was measured through written tests and hours-in-training. Everyone trained for the same duration. With simulators students can be trained to a measured level of proficiency.																

Hypothesis 4: Game-based training reduces the number of errors made by practitioners.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Aggarwal	2006		X	X	X	X	X										MIST-VR can measurably improve student performance.
Park	2002				X	X				X				X	X	X	Experienced lap surgeons believe that students need many more repetitions of procedures than they are receiving in the residencies. There is difficulty in establishing standards that can be fit into the current curriculum.
Marshall	2001				X				X	X	X						HPS devices improve trauma management by 23% in treatment decisions, 25% in adverse outcomes, and 47% in team behaviors. Also improve student self-confidence scores.
Hamilton	2002				X	X	X			X	X						In a study comparing VR to video-based training, only VR improved performance in real operative performance.
Stefanidis	2007				X	X				X							Proficiency-based simulator training improves operative performance. However, increasing the complexity of the training does not correspondingly increase performance in practice.
Ahlberg	2002				X	X	X			X							MIST-VR did NOT improve student performance in this study.
Ali	2002		X		X	X	X			X							VR provides measurable improvement in high school honors students used in experiments.
Ballantyne	2002				X									X	X		Great background on the evolution of medical education and laparoscopic surgery.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Brunner	2005	X	X	X	X	X	X			X	X						Students need new forms of training to achieve proficiency under current regulations on work hours.
Chaudhry	1999			X	X	X	X				X	X			X		MIST-VR determines proficiency based on error rates and time taken to complete tasks.
Enochson	2004			X	X	X	X			X	X	X					Experience with computer games improves simulator performance, which in turn improves surgical performance.
Frost	2004	X		X	X					X	X						Research into cost/benefits of AccuTouch VR laparoscopic simulator.
Gallagher	2001			X	X	X	X			X	X						Laparoscopic surgeries can be long and test the stamina of the surgeon. MIST-VR can be used to develop stamina prior to real surgery. Like a workout for surgical skills.
Gallagher	2004			X	X	X	X			X	X						MIST-VR can distinguish between experts and novices. It can also identify those who will have trouble developing the necessary psychomotor skills.
Gallagher	1999				X	X	X			X	X						MIST-VR can train novices in the "fulcrum effect" that reverses hand motions in laparoscopic surgery.
Gallagher	2002				X	X	X			X	X						MIST-VR contains metrics that allow objective measurement of proficiency.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Gor	2003				X	X	X				X	X					MIST-VR host computer data for comparison with gaming machines. Medical device runs on a generation of hardware that is 5 years behind other industries.
Grantcharov	2003	X	X	X	X	X	X			X	X						It takes 10-30 operations for a lap surgeon to master skills.
Grantcharov	2003		X	X	X	X	X			X	X						Training with MIST-VR allows students to perform surgery faster and with fewer errors.
Grantcharov	2001				X	X	X			X	X	X					MIST-VR can predict the skill that will appear in surgery.
Huang	2005			X	X	X	X			X	X	X					Laparoscopic surgery has three times more errors than open surgery. This is not decreasing with time. Game technology, especially 3D visualization engines can improve identification of internal anatomy. Very good argument for games. Very good support for using simulators to reduce errors on live patients.
Jordan	2001		X	X	X	X	X			X	X						Compares MIST-VR, Box trainer, and nothing. MIST-VR is best.
Jordan	2000			X	X	X	X			X	X	X					VR training leads to faster training, better instrument manipulation, and better visual identification. Most errors occur in first 10 operations.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Korndorffer	2006	X	X		X	X	X			X	X						88% consider VR skills labs effective at improving OR performance. But only 55% have such labs.
Kotharl	2002		X		X	X	X			X	X						MIST-VR is equivalent to the Yale Skills Course (5-day training).
Madan	2007		X	X	X	X	X			X	X			X			No difference between Box and VR training.
Madan	2005			X	X	X	X			X	X						MIST-VR comparisons with porcine training. Each skill acquired in 10 minutes.
Maithel	2006		X	X	X	X	X			X	X						VR holds great promise, but "current" (older) interface limits evaluation.
McNatt	2001	X			X	X	X			X	X						MIST-VR training leads to faster surgery and fewer errors.
Nehring	2001				X					X	X			X			The Human Patient Simulator has been used to provide nursing education in multiple skills. The author lists advantages of the system on page 198.
Pearson	2002	X	X		X	X	X			X	X	X					Quotable paragraph. MIST-VR and Box trainers are good for teaching knot tying skills
Reilly	2008			X	X	X				X		X					Playing games improves laparoscopic performance.
Rosser	2007	X			X					X	X	X			X		Medical error data. Video game skills correlate with laparoscopic skills.
Schijven	2005		X		X	X	X			X	X						MIST-VR and LapChol improve lap skills more than other methods.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Schwid	2001				X						X	X		X	X		Introduces the Advanced Cardiac Life Support (ACLS) program of instruction and its ability to evaluate people based on their skills rather than knowledge.
Seymour	2002			X	X	X	X			X	X	X					VR training increases speed and reduces errors in gall bladder surgery.
Shalhav	2002			X	X									X	X		Rapid popularity of laparoscopic surgery created a shortage of trained doctors.
Stefanidis	2006			X	X	X				X							Laparoscopic surgical procedures contain a number of limitations that require practice to master. The "fulcrum effect" in which a surgeon’s movements are reversed by the orientations of instruments through the abdominal wall is a commonly cited example.
Torkington	2001				X	X	X			X	X						MIST-VR does improve learning in laparoscopic surgery.
Torkington	2001				X	X	X			X	X						MIST-VR does improve learning in laparoscopic surgery.

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
Summary:	(Grantcharov, 2003) Students trained with MIST-VR achieve proficiency faster and make fewer errors in real surgery. (Madan, 2003) Game skills are positively correlated with lap skills. (Frost, 2004) AccuTouch can get students to proficiency for surgery faster. (Adamsen, 2004) VR systems can identify who is experienced, can be used as a tool for certification and end of training. (Brunner, 2004) MIST-VR can support measurable proficiency. (Chaudhry, 1999) Measurable error rate indicates proficiency objectively. (Gallaher, 2001) Laparoscopic surgery requires stamina, which can be developed through repeated use of simulators. (Huang, 2005) Laparoscopic surgery has high error rates and these have not decreasing over time. Need a new means of improving skill, especially in identifying internal anatomy. VR allows visualization and repetition. (Jordan, 2000) VR leads to faster proficiency, better visual identification. (Madan, 205) Shows that a skill can be learned in 10 minutes in either VR or porcine training. (Stefanidis, 2006) Lap surgery requires repetition to master skills. (Seymour, 2002) VR leads to faster skill development. (Shalhav, 2002) Explosive popularity of laparoscopic surgery led to a crisis of skilled surgeons. How to provide large volume proficiency?																
Analysis:	There is a great deal of evidence that errors are most common in the first 10-30 surgeries and that VR and simulators allow residents to train in an environment that is tolerant of errors until proficiency is reached.																
Non-Laparoscopic References																	
Abrahamson								X		X	X						Description of the Sim One device of 1969. Core reference in this field.
Abrahamson	1997										X				X		History of Sim One beginning in 1967. Computers being explored that early.
Aggarwal	2006		X		X									X			Simulation allows risk-free training and predictable availability.
Alinier	2006				X									X			Performance improved with simulation.

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
Alinier	2006									X							Some cost data, one reference on effectiveness of mannequins.
Andrea											X						Mastoidectomy simulator with visual and haptic feedback.
Berman	2003													X			Describes use of role playing exercises to rehearse activities in an emergency.
Bielser												X					Describes necessary 3D physical modeling to support open surgery, with haptics.
Binstadt	2007	X	X		X									X			Simulator Categories: mannequin, microsim, partial-task. Includes cost data on these. Multiple references to other useful sources.
Birden	2007													X			Time is an issue in scheduling training with facilities and faculty.
Boyd	2006					X				X	X						Subjective evaluations of training with simulations.
Bridges	1999	X								X					X		Analysis of financial cost of teaching residents in the OR vs. in a simulator.
Brown	2006											X					Describes the design of a VR operating room.
Byrne	2001				X			X		X							Premature to use simulators for certification of anesthesiologists. Games and VR are categorized as high-fidelity simulation.
Cates	2007								X		X						Vascular simulator has similar behaviors to real body.
Chuang	2005									X	X	X					Using VR to rehabilitate patients after surgery. Uses VR treadmill and bicycle.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Cohen	2006									X	X						VR for skills development in colonoscopy.
Dankelman	2005			X										X	X	x	Learning on patients is not good for patients or doctors. Reduced training time using simulators.
Dankelman	2005					X								X	X		"See one, do one, teach one" (Halsteadian Philosophy), is only appropriate for simple surgeries. Minimally invasive procedures (laparoscopic and others) are too complex for this.
Davis	1995									X					X		Conferences are very poor for continuing medical education, systematic practice-based interventions are better at changing behaviors in surgeons.
Davis	1999									X					X		Continuing medical education requires opportunities to practice skills.
Debas	2005													X			Major study that is driving changes to medical education.
DeLeo	2003										X	X					High-end sim with 3D shutter glasses, game tech heavily used for 3D, in world models.
Denson	1969							X			X				X		Great historical paper on Sim One, the first anesthesia simulator.
Dunkin	2007	X	X			X	X				X	X					Surgical simulation review: cost data, demand of surgeons, games extend training.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Enochson	1990															X	Current economic environment limits training on patients - 1) decreasing hospitalization periods, 2) increased acuity of illness, 3) increased sensitivity to patient right to privacy.
Erez	2007													X	X		Describes the current environment that makes VR/sim-based training attractive.
Eversbusch	2004				X					X	X						Improved performance on colonoscopy using GI mentor simulator.
Gaba	1992							X	X				X				Anesthesia training is a puzzle in which different methods provide different pieces that interlock.
Garden	2000				X					X	X						Simulations can reduce errors on patients, improve skills, and move practice off of patient.
Gerson	2003	X	X	X		X				X	X						Demonstrated that VR system is inferior to bedside teaching technique. But assumes that live training has access to the symptom.
Good	2003	X	X					X			X				X		Simulators allow the presentation of rare symptoms which are seldom presented by live patients.
Gordon	2005								X					X			Standardized patients used to teach emergency stroke.
Haluck	2005										X						Provides a high-level diagram of the components of a medical simulator.
Halvorsen	2005					X	X				X						Introduces examples of VR and simulators in surgery training.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Hoffman	1975	X						X			X						Summarized 21 different studies on Sim One and its effectiveness in teaching intubation, anesthesia, injection, recovery room care, and pulse/respiration evaluation.
Holm	1998		X									X					Simulators allow learners to take initiative for their own education.
Holtscheider	2007													X			44,000 to 98,000 people die each year due to medical error. Partially due to poor communication and poor teamwork, skills that can be rehearsed in a virtual OR.
Howard	1992							X						X			65-70% of all errors in anesthesia are due to human error. Anesthesiologists have crises situations very rarely and are not prepared for them. They can be trained in these situations with a simulator.
Hu											X						Describes mechanical design of a haptic open surgery simulator. Device includes game technology for motion capture, visualization, and physics.
Issenberg	2007			X		X		X	X	X							Repetition in simulators improves performance in real surgery for laparoscopy, anesthesia, and cardiology.
Issenberg	2005				X					X							Provides 10 useful characteristics of simulation for training

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
Kneebone	2001													X		X	Ethically unacceptable to gain experience on real patients.
Kneebone	2003											X		X			Simulators are classified as model-based, sim-based, and hybrid. Also computer/VR systems are gaining acceptance.
Kuppersmith	1997	X			X						X						Engineering design for a dissection simulator
Kurrek	1997	X						X			X						Cost data on building a simulation center for a hospital - includes mannequins and VR.
Kyrkjebo	2006													X	X		Simulators allow team training and the presentation of rare events.
Lasater	2007													X	X		Interactivity of simulators motivates students. Active role of students promotes better learning. Allows making mistakes as a form of learning.
LeBlang	1997													X			Mock trial role playing simulation to prepare doctors for court appearance.
Liaw	2002										X						Web-based learning environment. This will soon be augmented with 3D game environments.
Mantovani	2003												X				Visionary statement "VR represents a promising area with high potential of enhancing and modifying the learning experience …"

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
McDougall	2007	X		X													Surgical complexity is exceeding the ability of traditional methods of teaching. Survey of simulator progress. Great Quotes.
McGaghie	2006									X				X	X		Lists 10 educational features of simulations.
Murphy	2007			X											X		Great Quotes. Four criteria, advantages, and taxonomy of simulation.
Murray	2002			X				X		X							Simulators allow measurement and a reduction in training time since proficiency can be measured.
Murray	2004				X			X		X	X						Mannequin sims can be used to measure proficiency in complex skills.
Mutter	2005										X		X				Websurg.com web site contains online courses.
Owen	2002			X				X								X	Ethics of intubating patients to teach students. Students can learn on sim in 75-90 minutes. Issues with cadavers and animals make them less than ideal learning tools.
Poss	1999			X		X					X						"Arthroscopy of the knee is an ideal model for emulation because the surgeon is already performing the procedure in a quasi-virtual environment."
Reznick	2006					X								X			3-stage theory of motor skills acquisition: Cognition, Integration, Automation

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Rhyne	2002												X				Simulation is a powerful tool for experience.
Riley	1997	X						X		X	X						Anesthesia simulator is considered expensive, best for education, not for certification.
Ritter	2005	X									X						Advanced Trauma Life Support courses have replaced their cadavers and animals with TraumaMan simulator in half of schools.
Robb	1997											X					Endoscopes need 3D modeling and physics to create tools that familiarize before real operation
Rogers	2002				X	X								X	X	X	Availability of lap cholecystectomy led to increased demand. This led to rapid seminar-based learning, practice on patients, and high error rates
Rolfsson	2002	X	X	X	X	X					X	X					Game-based sims can improve hand-eye coordination. Need geometric models.
Sarker	2007	X	X	X	X	X					X	X					Numerous advantages of simulators listed. Real-time feedback is powerful.
Satava	2007				X						X		X				Visionary paper on VR that includes specific patient data.
Satava	2005														X		Simulators are useful in identifying errors in a safe environment.
Satava	1997					X						X	X				VR is useful for planning surgeries before doing them. May eventually be able to insert data from specific patients prior to operation on that patient.

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
Satava	2005												X		X		Summary history of modern military surgery - 19th, 20th, 21st centuries.
Satava	2005	X		X						X			X		X		M&S is part of the new scientific methods - simulate before you experiment.
Satava	2004	X	X	X	X							X			X		Reduced financial support of medical education, partially driven by insurance restrictions which reduce hospital stay and reduce profits to be spent on education.
Satava	2004												X				Future predictive simulation will involve running experiments on supercomputers with data from one million patients over 50 years.
Schijven	2005					X											A valid VR simulator must be able to mimic visual-spatial ability and real-time characteristics of the procedure, while providing realistic haptic feedback.
Selder	2006													X			Older generation of physicians exploit the younger generation via seniority pay and higher standards in medical education.
Seybert	2006									X	X						Students satisfied by training in cardio infarction with Sim-Man.
Seymour	2005	X			X	X	X			X	X						MIST-VR training improved student speed in suturing as compared to control group.
Spencer	2006										X						Simulations enable team training and enhance patient safety.

Source		Hypothesis				Specialty				Nature and Content							
Author	Year	H1	H2	H3	H4	L	M	A	C	S	D	G	F	Ed	B	Eth	Comment
Spitzer	1997										X				X		Beyond the Surgeon - "The majority of health care professionals do not have firsthand cadaver experience and derive their perception of the human body from textbooks and classical didactic materials."
Stafford	2005													X			Stage acting as a tool in medical education.
Stimmel	2006										X			X			Standardized patient is a human simulator for training. Introduced in 1963.
Sutherland	2006	X			X		X			X							Great survey of simulator papers. Includes cost data. Argues that simulator training is not better than traditional methods. Assumes student will have access to the symptoms during their training.
Thacker	2003								X		X						Simantha includes tactile feedback for catheter insertion.
Tsai	2001										X						VR orthopedic sim replaces 2D image preparation with 3D volume preparation.
Uchal	2005				X	X				X	X						Laparoscopic surgery skills can be learned through 6-task simulation model.
VanSickle	2007			X		X	X				X				X		MIST-VR is a widely accepted laparoscopic training sim. It uses 3D visualization game technology.

Source		Hypothesis				Specialty				Nature and Content							
Author	**Year**	**H1**	**H2**	**H3**	**H4**	**L**	**M**	**A**	**C**	**S**	**D**	**G**	**F**	**Ed**	**B**	**Eth**	**Comment**
Viciana-Abad	2004										X						Degree of presence in sim is driven by (1) natural interaction, and (2) complexity of patient modeling.
Wallace	1997										X			X			Great history of the Standardized Patient.
Wantman	2003							X			X						200 Human Patient Simulators in use in 2003, classified as a high-fidelity simulator.
Waseda	2005		X			X					X						Some European countries (e.g. UK) prohibit use of live animals in teaching. This box trainer uses animal organs and overcomes the "live" issue.
Wayne					X				X	X							Training on a medical simulator dramatically increased the skills of residents in ACLS.
Weller	2003							X		X							Simulation is more effective at changing practice than is didactic learning.
Ziv	2003	X												X	X	X	The use of sim-based training is an ethical imperative. Given the adoption of sims in other high-hazard professions, it is unethical not to use this in medicine
Ziv	2005				X									X			Sim-based training allows students to learn though experience with errors, something that is not intentionally possible when practicing on live patients

Appendix 2. Medical VR and Simulation Vendors in the Literature Reviewed

Source		Hypothesis				Specialty			Nature			
Company	Product	H1	H2	H3	H4	L	A	C	S	G	B	Comment
Laparoscopic Devices												
Dome Medical	no info											no info available
Haptica	ProMIS		X	X	X	X			X	X		Used in FLS Courses. Measures instrument path length, smoothness of motion. Aug Reality adds to objective measurement.
Haptica	ProMIS-J		X		X	X						Junior version allows individuals to take home and use in classroom
Immersion Medical	Laparoscopy AccuTouch	X			X							Frost & Sullivan study on financial ROI is very useful
Immersion Medical	Laparoscopy VR	X	X	X	X	X						Many movies on the use of the system. Great samples of 3D and physics modeling
Laparoscopy Hospital	multiple											Training facility for lap surgery
Mentice	MIST-VR		X	X	X	X			X	X		Extensive studies on effectiveness
Mentice	Sammy											no info available
METI	SurgicalSim		X	X	X	X				X		Endoscopic robotic sim with stereo view. Prostate, Lap, Cholecestectomy
Penn State Medical School	Sim List w/ Descriptions											Great list of sims used at PSU Medical School and descriptions of each

Source		Hypothesis				Specialty			Nature			
Company	**Product**	**H1**	**H2**	**H3**	**H4**	**L**	**A**	**C**	**S**	**G**	**B**	**Comment**
RealSim Systems	no info											Basic lap trainer. Mostly rubber tactiles
Sawbones	Alex											no info available
SCOI Classroom	multiple					X				X		Courses in laparoscopic surgery, uses Alex, Sammy, Misty
Simbionix	LAP Mentor								X			Typical VR lap training in a standup device
Simbionix	GI Mentor								X			Typical VR GI training in a standup device
Simlab	SimuVision											Combined VR computer and tactile material trainer
Surgical Science	LapSim								X	X		VR-based lap sim. Similar to MIST
The SIM Group @ CIMIT	CELTS					X			X			Computer/Mechanical device for measuring lap movement
Verefi Technologies	EndoTower, Head2Head, LapFast											H2H is a game-based skills trainer that uses competition to motivate practice
Xitacts	LapChol											Company went out of business. Sold patents to Mentice, where they were used for a new version of MIST-VR
Non-Laparoscopic Devices												
Center for Research in Medical Sim	Harvey											no info

Source		Hypothesis				Specialty			Nature			
Company	**Product**	**H1**	**H2**	**H3**	**H4**	**L**	**A**	**C**	**S**	**G**	**B**	**Comment**
Computer Motion	AESOP, HERMES, ZEUS											Company seems to be defunct
Energid MGH	Open Surgery Sim											Open Surgery simulation developed for the Army
Medical Simulation Corp	Simantha											A mannequin that is now part of a larger product SimSuite
Medical Simulation Corp	SimSuite											Medical training program using sims
METI	Human Patient Sim	X	X		X		X	X	X			Emergency preparedness simulations. Rare event prep.
METI	BabySim											
METI	Pelvic ExamSim											
METI	PediaSim											
METI	Gainesville Anesthetic Sim											
Minimally Invasive Surgical Training Centre	Tuebingen MIC-Trainer											Training facility/program that is associated with the MIC device
n/a	Sim-One											Original 1967 medical simulator for anesthesiology
ProSim	mechanical devices								X			Simulators to wear-test prosthetic devices

Appendix 3. Personal Communication in Support of Dissertation Topic

Date	Practitioner	Position	Method	Discussion Topic
13-Mar-00	John Laird	Professor, Dept. of Computer Science, University of Michigan	Meeting	Laird said that computer game developers adopt new advances in AI much faster than do defense projects. Typically you have to wait 5 years to see a new idea implemented in a defense system. The gaming industry will incorporate a new technique into a project within one year. You also get to see how it works for thousands of customers very quickly.
10-Jan-08	Richard Satava	Professor, Dept. of Surgery, University of Washington	Telecon	Dr. Richard Satava is a researcher, pioneer, and the author of several papers in this field. He has also edited special journal issues on using simulation/VR for medical training. He developed the first VR system for medical training along with Jaron Lanier in the early 1990's. He felt that at that time VR was 10 years away from really being applicable to medical training. We discussed the transition of military simulation technology to the medical field.
10-Jan-08	David Thompson	Project Director, Army Medical Simulation Training Centers	Meeting	Met with MAJ Thompson who manages the creation and operation of 18 medical training facilities for the Army. These facilities primarily use the METI Human Patient Simulator (a mannequin) and the Tactical Combat Casualty Care system (a computer game).

Date	Practitioner	Position	Method	Discussion Topic
6-Feb-08	Rick McKenzie	Professor, IE and Simulation, Old Dominion University	Meeting	This week I was part of a team that was giving demonstrations of a number of military simulators at both the Senate and House office buildings on Capitol Hill. These demos included 4 medical training devices, two of which incorporated games or game technology. (I have pictures of all of them to upload later.) a. Human Patient Simulator. This is the leading device for anesthesia training in both civilian and military medical schools and programs. The Army uses the device to each combat medic to treat a couple of the most life threatening injuries that occur on the battlefield and which can be treated prior to arrival at a hospital. b. Combat Tourniquet Simulator. This is rubber arm that contains electronics that simulate the blood flow in different sizes of human arms and different severity of wounds. It simply teaches a medic how tightly to close a tourniquet to stop blood flow. The device is being integrated with a combat & medical computer game to allow the medic to play a bigger combat role in the game, switch out to tactile training with the arm, then go back to other tasks in the game. Medics currently practice this skill on a 4X4 piece of wood. c. Augmented Standardized Patient. A standardized patient is an actor who is trained to present certain symptoms as accurately as possible. However, problems with irregular heartbeat and plaque inside of arteries create symptoms that can be heard in a stethoscope. This simulator attaches a wireless device to an electronic stethoscope so that a computer will insert irregular heart or blood flow sounds into the stethoscope. d. Wound Diebriedmant with Haptic Feedback. This presents a 3D image of a human arm that has a significant

Date	Practitioner	Position	Method	Discussion Topic
				wound with glass embedded in it. The student must use tweezers to remove the glass, a brush to clean away debris, and a syringe to wash the wound and add disinfectant. These are all controlled with a haptic device that gives feedback to students understand the amount of force that must be applied. Students must overcome the lack of stereoscopic view.

Date	Practitioner	Position	Method	Discussion Topic
14-Feb-08	Stephen Snyder	Owner & Instructor, SCOI CLASroom, Continuing Medical Education in Laparoscopic Surgery		He uses cadaver parts and simulators in these classes. • On cadavers vs. simulators he says, "It is a very unpleasant way to learn and the experience is very marginal. Once you do one operative procedure on cadaver part, you can't do it again. But with a virtual reality simulator or lifelike model, procedures can be performed over and over until the student masters the task."

Date	Practitioner	Position	Method	Discussion Topic
16-Feb-08	Richard Satava	Professor, Dept. of Surgery, University of Washington	Email	H1: Simulator/VR systems present a cost advantage over other methods of training in laparoscopic surgery. (Especially animal and cadaver labs.) Response: True, but they are not sophisticated enough yet to do more than entrance-level training. H2: Simulator/VR systems enable increased access by students to specific patient symptoms. (Regulations limiting student working hours in the hospital are increasing this.) Response: True also. The 80 hour work week is killing medical education. Simulators that are designed with criterion to reach (similar to game), with error checking and immediate feedback (formative feedback) are very good. Once again the problem is that at this time the simulators are quite simplistic H3: Simulator/VR systems reduce the time necessary to train laparoscopic skills to proficiency. (By offering metric-based training, students can stop when measured to be competent in a skill.) Response: True as above H4: Simulator/VR systems reduce the number of surgical errors on live patients. (The learning curve occurs on the simulator rather than on patients.) Response: True - that was our Yale study that provided prospective randomized proof that simulation reduces errors. In addition to the literature search I have done, I would like to find some practitioner information. Like: 1) Which medical schools are most progressive in adopting

Date	Practitioner	Position	Method	Discussion Topic
				simulators and VR? Response: A number, such as Beth Israel Deaconess (Harvard) Medical Center, and our own ISIS simulation center at Univ Washington. There is a list of the 28 American College of Surgeon certified centers, which are among the most progressive. http://www.facs.org/education/accreditationprogram/list.html 2) Which product vendors are the most scientifically objective in developing these devices? Response: There are only a few. However METI in Tampa is near the top. Simbionix and Immersion each have excellent endoscopy simulators, and Mentice has a great endovascular simulator. 3) Which medical specialties are most appropriate for VR systems? Is laparoscopic surgery one of the best? Response: Laparoscopic surgery is the easiest to do simulation for because it does surgery by looking at a video monitor. Robotic surgery is also a natural, though not as many of these have been made. Any surgical procedure that uses a monitor to visualize the procedure that is being performed has a very decided advantage. Other companies (Laerdal and Simulab along with METI) have some very good manikin based simulators. 4) Looking to the future is there some other technology that holds more promise for improving the training of surgeons? Response: I don't know of another. We use didactic lectures (pedagoguery), case-based scenarios (computer generated), patient actors, simulation (manikin, computer, virtual reality). If there are any other technologies, I would

Date	Practitioner	Position	Method	Discussion Topic
				be happy to learn about them.

Date	Practitioner	Position	Method	Discussion Topic
22-Feb-08	Richard Satava	Professor, Dept. of Surgery, University of Washington	Meeting	a. Dr. Richard Satava attended the meeting at the Nicholson Center. He made several strong statements in support of VR in training doctors. i. “The Achilles heal of medical education is faculty time. These people are in the OR generating revenue per hour and do not have time to teach students.” This is why medical schools need computer-assisted training tools that can measure student performance when experienced surgeons are not available. ii. “The new President of the American College of Surgeons has set surgical simulation as his priority for the next 2 years.” He says that each President promotes a few key agenda items during their 2 year term and we have the opportunity to take advantage of the new President’s focus. iii. “The ACGME has stated that every training center must have access to simulators for surgical skills by July 2008.” (ACGME = Accreditation Council for Graduate Medical Education). As a result every single medical school that Satava has visited has simulation as one of their top three priorities. iv. “The medical profession goes through a revolution about every 100 years. The last one was with the Flexner Report of 1908 that established the current apprenticeship model for training surgeons. Simulation is creating the next revolution.”

Date	Practitioner	Position	Method	Discussion Topic
22-Feb-08	Rick Wassel	Administrative Director, Florida Hospital, Nicholson Surgical Center	Meeting	“Simulators can strengthen core surgical skills with instruments. Simulations that explore rare situations can turn good surgeons into outstanding surgeons.” This was also in the context of comparisons with military simulation. He also described the porcine lab as Celebration Health with some background on why these animals are the "gold standard" for surgical training.
22-Feb-08	Vipul Patel	Director of Global Robotics Institute, Florida Hospital, Nicholson Surgical Center	Meeting	“We find that mastering advanced skills leads to better daily practice. It improves all skills.” This was during a conversation about how the military uses simulators to teach critical, life threatening skills to pilots. The pilot may experience these situations only once during a career, but they are prepared for it. Patel Web Site: http://www.globalroboticsinstitute.com/urology-robotic-prostatectomy
26-Feb-08	Richard Satava	Professor, Dept. of Surgery, University of Washington	Email	Discussed the lack of presence of a medical robot in the Army's Future Combat System. Also, surgeons do not have good training in teamwork in the OR, something that is a core training area in military team simulators.

Date	Practitioner	Position	Method	Discussion Topic
17-Mar-08	Richard Satava	Professor, Dept. of Surgery, University of Washington	Meeting	Medical haptic feedback requires 1KHz sampling rate. This is much higher than for visual stimulation. The availability of faculty is the primary limiting factor in providing medical education to residents. Residents are limited to an 80 hour work week and are paid about $40,000. Dimitry Olynekov (Univ Nebraska) and Danny Scott (Univ of Texas Southwestern) are creating tiny robots that can be inserted into the body to conduct surgery. Their small size makes it difficult for them to get leverage against tissue. They can be positioned via radio commands or dragged into place magnetically.
27-Mar-08	Richard Satava	Professor, Dept. of Surgery, University of Washington	Email	Discussed the debate over the meaning of vital signs in predicting the need for additional treatment. The discussion was motivated by two articles from the Journal of Trauma that proposed some new standards. Accurate interpretation of available vitals can mean the difference between life and death for patients.
20-May-08	Richard Satava	Professor, Dept. of Surgery, University of Washington	Meeting	Military modeling and simulation of open simulators, surface wound mapping, virtual autopsy. Richard is trying to expose us to the work that is being done in other organizations.
20-May-08	Howard Champion	Professor, Uniformed Health Medical Center	Meeting	Describes the systems that have been created by his company, SimQuest. Notable was a map of bullet entry, damage, and exit wounds. This was to serve as the valid data set to construct a training simulation that could accurately replicate these wounds.

Date	Practitioner	Position	Method	Discussion Topic
12-Jun-08	Miles Kitching	British Sales Manager, Mentice Products	Meeting	Mr. Kitching has worked in the medical simulation field for 14 years, including with the original creators of MIST-VR, Rory McCloy and Bob Stone. He described the history of the technology and the system from 1995 with the founding of Virtual Presence Inc. to market MIST-VR, through its acquisition by Mentice, and the acquisition of Xitact force feedback patents by Mentice. He also described the costs of developing software models of human tissue and its manipulation.
12-Jun-08	Thomas Nowak	President, Surgical Science USA	Meeting	Mr. Nowak discussed the training programs that are created to teach laparoscopic skills. His opinion is that there is no evidence that training with 3D models of organs builds better skills that working with generic 3D objects that are specifically designed to convey a skill. It is extremely expensive to build the visual and physics models of organs; therefore it is important for a company to know that these are necessary before investing in them.

References

VR for Laparoscopic Surgical Education

Adamsen, S., Funch-Jensen, P., Drewes, A., Rosenberg, J., & Grantcharov, T. (2005, February 2). A comparative study of skills in virtual laparoscopy and endoscopy. *Surgical Endoscopy*, *19*(2), 229-234. Retrieved January 21, 2008, from MEDLINE database.

Aggarwal, R., Grantcharov, T., Moorthy, K., Hance, J., & Darzi, A. (2006, January). A competency-based virtual reality training curriculum for the acquisition of laparoscopic psychomotor skill. *American Journal Of Surgery*, *191*(1), 128-133. Retrieved January 21, 2008, from MEDLINE database.

Aggarwal, R., Ward, J., Balasundaram, I., Sains, P., Athanasiou, T., & Darzi, A. (2007, November). Proving the effectiveness of virtual reality simulation for training in laparoscopic surgery. *Annals Of Surgery*, *246*(5), 771-779. Retrieved April 6, 2008, from MEDLINE database.

Ahlberg, G., Heikkinen, T., Iselius, L., Leijonmarck, C., Rutqvist, J., & Arvidsson, D. (2002, January 12). Does training in a virtual reality simulator improve surgical performance?. *Surgical Endoscopy*, *16*(1), 126-129. Retrieved January 21, 2008, from MEDLINE database.

Ali, M., Mowery, Y., Kaplan, B., & DeMaria, E. (2002, December 29). Training the novice in laparoscopy. More challenge is better. *Surgical Endoscopy*, *16*(12), 1732-1736. Retrieved January 21, 2008, from MEDLINE database.

Ballantyne, G., & Kelley, W. (2002, February). Granting clinical privileges for telerobotic surgery. *Surgical Laparoscopy, Endoscopy & Percutaneous Techniques*, *12*(1), 17-25. Retrieved February 13, 2008, from MEDLINE database.

Brunner, W., Korndorffer, J., Sierra, R., Massarweh, N., Dunne, J., Yau, C., et al. (2004, December). Laparoscopic virtual reality training: are 30 repetitions enough?. *The Journal Of Surgical Research*, *122*(2), 150-156. Retrieved January 21, 2008, from MEDLINE database.

Brunner, W., Korndorffer, J., Sierra, R., Dunne, J., Yau, C., Corsetti, R., et al. (2005, January). Determining standards for laparoscopic proficiency using virtual reality. *The American Surgeon*, *71*(1), 29-35. Retrieved January 21, 2008, from MEDLINE database.

Chaudhry, A., Sutton, C., Wood, J., Stone, R., & McCloy, R. (1999, July). Learning rate for laparoscopic surgical skills on MIST VR, a virtual reality simulator: quality of human-computer interface. *Annals Of The Royal College Of Surgeons Of England*, *81*(4), 281-286. Retrieved January 21, 2008, from MEDLINE database.

Cox, M. and Irby, D.M. (2006, September 28). A new series on medical education. *New England Journal of Medicine*, 355(13), 1375-1376.

Cuschieri, A. (1995, January). Whither minimal access surgery: tribulations and expectations. *American Journal Of Surgery*, 169(1), 9-19. Retrieved March 24, 2008, from MEDLINE database.

DeMaria, E., McBride, C., Broderick, T., & Kaplan, B. (2005, June). Night call does not impair learning of laparoscopic skills. *Surgical Innovation*, *12*(2), 145-149. Retrieved January 21, 2008, from MEDLINE database.

Derossis, A., Fried, G., Abrahamowicz, M., Sigman, H., Barkun, J., & Meakins, J. (1998, June). Development of a model for training and evaluation of laparoscopic skills. *American Journal Of Surgery*, *175*(6), 482-487. Retrieved March 16, 2008, from MEDLINE database.

Eastridge, B., Hamilton, E., O'Keefe, G., Rege, R., Valentine, R., Jones, D., et al. (2003, August). Effect of sleep deprivation on the performance of simulated laparoscopic surgical skill. *American Journal Of Surgery*, *186*(2), 169-174. Retrieved January 21, 2008, from MEDLINE database.

Enochsson, L., Isaksson, B., Tour, R., Kjellin, A., Hedman, L., Wredmark, T., et al. (2004, November). Visuospatial skills and computer game experience influence the performance of virtual endoscopy. *Journal Of Gastrointestinal Surgery: Official Journal Of The Society For Surgery Of The Alimentary Tract*, *8*(7), 876. Retrieved January 21, 2008, from MEDLINE database.

Frost & Sullivan. (2004). Return on investment study for medical simulation training: Immersion Medical, Inc. Laparoscopy AccuTouch System. Industrial research report available at: http://www.immersion.com/medical/products/laparoscopy/roi/FS_IMMRmed_laparoscopy_ROI_V2.pdf

Gallagher, A., & Satava, R. (2002, December 29). Virtual reality as a metric for the assessment of laparoscopic psychomotor skills. Learning curves and reliability measures. *Surgical Endoscopy*, *16*(12), 1746-1752. Retrieved January 21, 2008, from MEDLINE database.

Gallagher, A., Lederman, A., McGlade, K., Satava, R., & Smith, C. (2004, April 19). Discriminative validity of the Minimally Invasive Surgical Trainer in Virtual Reality (MIST-VR) using criteria levels based on expert performance. *Surgical Endoscopy*, *18*(4), 660-665. Retrieved January 21, 2008, from MEDLINE database.

Gallagher, A., Richie, K., McClure, N., & McGuigan, J. (2001a, November). Objective psychomotor skills assessment of experienced, junior, and novice laparoscopists with virtual reality. *World Journal Of Surgery*, *25*(11), 1478-1483. Retrieved January 21, 2008, from MEDLINE database.

Gallagher, H., Allan, J., & Tolley, D. (2001b, November). Spatial awareness in urologists: are they different?. *BJU International*, *88*(7), 666-670. Retrieved January 21, 2008, from MEDLINE database.

Gor, M., McCloy, R., Stone, R., & Smith, A. (2003, February). Virtual reality laparoscopic simulator for assessment in gynaecology. *BJOG: An International Journal Of Obstetrics And Gynaecology*, *110*(2), 181-187. Retrieved January 21, 2008, from MEDLINE database.

Grantcharov, T., Bardram, L., Funch-Jensen, P., & Rosenberg, J. (2003b, July 6). Impact of hand dominance, gender, and experience with computer games on performance in virtual reality laparoscopy. *Surgical Endoscopy*, *17*(7), 1082-1085. Retrieved January 21, 2008, from MEDLINE database.

Grantcharov, T., Bardram, L., Funch-Jensen, P., & Rosenberg, J. (2003a, February). Learning curves and impact of previous operative experience on performance on a virtual reality simulator to test laparoscopic surgical skills. *American Journal Of Surgery*, *185*(2), 146-149. Retrieved January 21, 2008, from MEDLINE database.

Grantcharov, T., Kristiansen, V., Bendix, J., Bardram, L., Rosenberg, J., & Funch-Jensen, P. (2004, February). Randomized clinical trial of virtual reality simulation for laparoscopic skills training. *The British Journal Of Surgery*, *91*(2), 146-150. Retrieved December 27, 2007, from MEDLINE database.

Grantcharov, T., Rosenberg, J., Pahle, E., & Funch-Jensen, P. (2001, March 6). Virtual reality computer simulation. *Surgical Endoscopy*, *15*(3), 242-244. Retrieved January 21, 2008, from MEDLINE database.

Hamilton, E., Scott, D., Fleming, J., Rege, R., Laycock, R., Bergen, P., et al. (2002, March 10). Comparison of video trainer and virtual reality training systems on acquisition of laparoscopic skills. *Surgical Endoscopy*, *16*(3), 406-411. Retrieved March 16, 2008, from MEDLINE database.

Hyltander, A. (2003, June). Simulation as a teaching alternative: Utopia or reality. *CAL-aborate*, 10. Retrieved May 1, 2008 from http://science.uniserve.edu.au/pubs/callab/vol10/hyltand.html.

Huang, J., Payandeh, S., Doris, P., & Hajshirmohammadi, I. (2005). Fuzzy classification: towards evaluating performance on a surgical simulator. *Studies In Health Technology And Informatics*, *111*, 194-200. Retrieved January 21, 2008, from MEDLINE database.

Jordan, J., Gallagher, A., McGuigan, J., & McClure, N. (2001, October). Virtual reality training leads to faster adaptation to the novel psychomotor restrictions encountered by laparoscopic surgeons. *Surgical Endoscopy*, *15*(10), 1080-1084. Retrieved January 21, 2008, from MEDLINE database.

Jordan, J., Gallagher, A., McGuigan, J., McGlade, K., & McClure, N. (2000, September). A comparison between randomly alternating imaging, normal laparoscopic imaging, and virtual reality training in laparoscopic psychomotor skill acquisition. *American Journal Of Surgery*, *180*(3), 208-211. Retrieved January 21, 2008, from MEDLINE database.

Korndorffer, J., Dunne, J., Sierra, R., Stefanidis, D., Touchard, C., & Scott, D. (2005, July). Simulator training for laparoscopic suturing using performance goals translates to the operating room. *Journal Of The American College Of Surgeons*, *201*(1), 23-29. Retrieved March 16, 2008, from MEDLINE database.

Korndorffer, J., Stefanidis, D., & Scott, D. (2006, January). Laparoscopic skills laboratories: current assessment and a call for resident training standards. *American Journal Of Surgery*, *191*(1), 17-22. Retrieved January 21, 2008, from MEDLINE database.

Kothari, S., Kaplan, B., DeMaria, E., Broderick, T., & Merrell, R. (2002, June). Training in laparoscopic suturing skills using a new computer-based virtual reality simulator (MIST-VR) provides results comparable to those with an established pelvic trainer system. *Journal Of Laparoendoscopic & Advanced Surgical Techniques. Part A*, *12*(3), 167-173. Retrieved January 21, 2008, from MEDLINE database.

Leonard, D. (2008, June 9). GameStop racks up the points: Meet the people who run the store your kids never leave. *Fortune Magazine*, p. 109-112.

MacFadyen, B., Vecchio, R., Ricardo, A., & Mathis, C. (1998, April). Bile duct injury after laparoscopic cholecystectomy. The United States experience. *Surgical Endoscopy*, *12*(4), 315-321. Retrieved March 16, 2008, from MEDLINE database.

Mackay, S., Morgan, P., Datta, V., Chang, A., & Darzi, A. (2002, June 26). Practice distribution in procedural skills training: a randomized controlled trial. *Surgical Endoscopy*, *16*(6), 957-961. Retrieved January 21, 2008, from MEDLINE database.

Madan, A., & Frantzides, C. (2007, January). Substituting virtual reality trainers for inanimate box trainers does not decrease laparoscopic skills acquisition. *JSLS: Journal Of The Society Of Laparoendoscopic Surgeons / Society Of Laparoendoscopic Surgeons*, *11*(1), 87-89. Retrieved January 21, 2008, from MEDLINE database.

Madan, A., Frantzides, C., & Sasso, L. (2005a, February). Laparoscopic baseline ability assessment by virtual reality. *Journal Of Laparoendoscopic & Advanced Surgical Techniques. Part A*, *15*(1), 13-17. Retrieved January 21, 2008, from MEDLINE database.

Madan, A., Frantzides, C., Shervin, N., & Tebbit, C. (2003, December). Assessment of individual hand performance in box trainers compared to virtual reality trainers. *The American Surgeon*, *69*(12), 1112-1114. Retrieved January 21, 2008, from MEDLINE database.

Madan, A., Frantzides, C., Tebbit, C., & Quiros, R. (2005b, June). Participants' opinions of laparoscopic training devices after a basic laparoscopic training course. *American Journal Of Surgery*, *189*(6), 758-761. Retrieved January 21, 2008, from MEDLINE database.

Maithel, S., Sierra, R., Korndorffer, J., Neumann, P., Dawson, S., Callery, M., et al. (2006, January 7). Construct and face validity of MIST-VR, Endotower, and CELTS: are we ready for skills assessment using simulators?. *Surgical Endoscopy*, *20*(1), 104-112. Retrieved January 21, 2008, from MEDLINE database.

McClusky, D., Ritter, E., Lederman, A., Gallagher, A., & Smith, C. (2005, January). Correlation between perceptual, visuo-spatial, and psychomotor aptitude to duration of training required to reach performance goals on the MIST-VR surgical simulator. *The American Surgeon*, *71*(1), 13. Retrieved January 21, 2008, from MEDLINE database.

McNatt, S., & Smith, C. (2001, October). A computer-based laparoscopic skills assessment device differentiates experienced from novice laparoscopic surgeons. *Surgical Endoscopy, 15*(10), 1085-1089. Retrieved January 21, 2008, from MEDLINE database.

Moorthy, K. et al. (2006, July). Surgical crisis management skills training assessment: A Stimulation-based approach to enhancing operating room performance. *Annals of Surgery*, 244(1), 139-147.

Murray, D. (2005, December). Clinical simulation: measuring the efficacy of training. *Current Opinion In Anaesthesiology, 18*(6), 645-648. Retrieved March 7, 2008, from MEDLINE database.

Park, A., Witzke, D., & Donnelly, M. (2002, May). Ongoing deficits in resident training for minimally invasive surgery. *Journal Of Gastrointestinal Surgery: Official Journal Of The Society For Surgery Of The Alimentary Tract*, 6(3), 501. Retrieved March 24, 2008, from MEDLINE database.

Pearson, A., Gallagher, A., Rosser, J., & Satava, R. (2002, January 12). Evaluation of structured and quantitative training methods for teaching intracorporeal knot tying. *Surgical Endoscopy*, *16*(1), 130-137. Retrieved January 21, 2008, from MEDLINE database.

Pham, T., Roland, L., Benson, K., Webster, R., Gallagher, A., & Haluck, R. (2005). Smart tutor: a pilot study of a novel adaptive simulation environment. *Studies In Health Technology And Informatics, 111*, 385-389. Retrieved January 21, 2008, from MEDLINE database.

Rattner, D., Apelgren, K., & Eubanks, W. (2001, October). The need for training opportunities in advanced laparoscopic surgery. *Surgical Endoscopy,* 15(10), 1066-1070. Retrieved March 24, 2008, from MEDLINE database.

Rosenberg, B., Landsittel, D., & Averch, T. (2005, April). Can video games be used to predict or improve laparoscopic skills?. *Journal Of Endourology / Endourological Society*, *19*(3), 372-376. Retrieved January 21, 2008, from MEDLINE database.

Rosser, J., Lynch, P., Cuddihy, L., Gentile, D., Klonsky, J., & Merrell, R. (2007, February). The impact of video games on training surgeons in the 21st century. *Archives Of Surgery (Chicago, Ill.: 1960), 142*(2), 181. Retrieved January 21, 2008, from MEDLINE database.

Schijven, M., Jakimowicz, J., Broeders, I., & Tseng, L. (2005b, September). The Eindhoven laparoscopic cholecystectomy training course--improving operating room performance using virtual reality training: results from the first E.A.E.S. accredited virtual reality trainings curriculum. *Surgical Endoscopy, 19*(9), 1220-1226. Retrieved January 21, 2008, from MEDLINE database.

Schoetz, D. (2006, September 21). Evolving practice patterns in colon and rectal surgery. *Journal Of The American College Of Surgeons*, *203*(3), 322-327. Retrieved February 13, 2008, from MEDLINE database.

Scott, D., Bergen, P., Rege, R., Laycock, R., Tesfay, S., Valentine, R., et al. (2000, September). Laparoscopic training on bench models: better and more cost effective than operating room experience?. *Journal Of The American College Of Surgeons*, *191*(3), 272-283. Retrieved March 16, 2008, from MEDLINE database.

Seymour, N., Gallagher, A., Roman, S., O'Brien, M., Bansal, V., Andersen, D., et al. (2002, October). Virtual reality training improves operating room performance: results of a randomized, double-blinded study. *Annals Of Surgery*, *236*(4), 458. Retrieved January 21, 2008, from MEDLINE database.

Shalhav, A.L., Dabagia, M.D., Wagner, T.T., Koch, M.O., Lingman, J.E. (2002, May). Training postgraduate urologists in laparoscopic surgery: The Current challenge. *The Journal of Urology*, 167, 2135-2137.

Stefanidis, D., Sierra, R., Korndorffer, J., Dunne, J., Markley, S., Touchard, C., et al. (2006a, January). Intensive continuing medical education course training on simulators results in proficiency for laparoscopic suturing. *American Journal Of Surgery*, *191*(1), 23-27. Retrieved March 16, 2008, from MEDLINE database.

Stefanidis, D., Korndorffer, J., Black, F., Dunne, J., Sierra, R., Touchard, C., et al. (2006b, August). Psychomotor testing predicts rate of skill acquisition for proficiency-based laparoscopic skills training. *Surgery*, *140*(2), 252-262. Retrieved January 21, 2008, from MEDLINE database.

Stefanidis, D., Korndorffer, J., Markley, S., Sierra, R., Heniford, B., & Scott, D. (2007, August 27). Closing the gap in operative performance between novices and experts: does harder mean better for laparoscopic simulator training?. *Journal Of The American College Of Surgeons*, *205*(2), 307-313. Retrieved March 16, 2008, from MEDLINE database.

Torkington, J., Smith, S., Rees, B., & Darzi, A. (2001, October). The role of the basic surgical skills course in the acquisition and retention of laparoscopic skill. *Surgical Endoscopy*, *15*(10), 1071-1075. Retrieved January 21, 2008, from MEDLINE database.

Torkington, J., Smith, S., Rees, B., & Darzi, A. (2001, October). Skill transfer from virtual reality to a real laparoscopic task. *Surgical Endoscopy*, *15*(10), 1076-1079. Retrieved January 21, 2008, from MEDLINE database.

General Medical Education and Virtual Reality

Abrahamson S., Denson J.S., Wolf R.M. (1969). Effectiveness of a simulator in training anaesthesiology residents. *Journal of Medical Education*, 44, 515–519

Abrahamson, S. (1997, Autumn). Sim One--a patient simulator ahead of its time. *Caduceus (Springfield, Ill.), 13*(2), 29-41. Retrieved December 27, 2007, from MEDLINE database.

Agency for Healthcare Research and Quality. (February 2000). *Medical errors: The scope of the problem: An epidemic of errors*. http://www.ahrq.gov/qual/errback.htm accessed March 15, 2008.

Aggarwal, R. and Darzi, A. (2006, December 21). Technical skills training in the 21st century. *New England Journal of Medicine*, 355(25), 2695-2696.

Alinier, G., Hunt, B., Gordon, R., & Harwood, C. (2006, May). Effectiveness of intermediate-fidelity simulation training technology in undergraduate nursing education. *Journal Of Advanced Nursing*, *54*(3), 359-369. Retrieved October 21, 2007, from MEDLINE database.

Bennett, N. (1994). Developmental perspectives in learning. In D. Davis and R. Fox (Eds), *The Physician as learner: Linking research to practice*. Chicago, IL: American Medical Association.

Berman, M.A. and Lazar, E.J. (2003, April 3). Hospital emergency preparedness – lessons learned since Northridge. New *England Journal of Medicine,* 348(14), 1307-1308.

Bielser, D., & Gross, M. (2002). Open surgery simulation. *Studies In Health Technology And Informatics*, *85*, 57-63. Retrieved December 27, 2007, from MEDLINE database.

Binstadt, E., Walls, R., White, B., Nadel, E., Takayesu, J., Barker, T., et al. (2007, April 11). A comprehensive medical simulation education curriculum for emergency medicine residents. *Annals Of Emergency Medicine*, *49*(4), 495. Retrieved December 27, 2007, from MEDLINE database.

Birden, H. and Page, S. (2007, August). 21st century medical education. *Australian Health Review*, 31(3), 341-350.

Boshuizen, H. and Schmidt, H. (1995). The development of clinical reasoning expertise. In J. Higgs and M. Jones (Eds), *Clinical reasoning in the health professions*. Boston, MA: Butterworth Heinemann.

Boyd, K., Olivier, J., & Salameh, J. (2006, June). Surgical residents' perception of simulation training. *The American Surgeon*, *72*(6), 521-524. Retrieved October 21, 2007, from MEDLINE database.

Bridges, M., & Diamond, D. (1999, January). The financial impact of teaching surgical residents in the operating room. *American Journal Of Surgery*, *177*(1), 28-32. Retrieved December 27, 2007, from MEDLINE database.

Byrne A.J. and Greaves J.D. (2001)Assessment instruments used during anaesthetic simulation: review of published studies. *British Journal of Anesthesiology* 2001; 86: 445–450.

Carey, J. (2006, May 26). Medical guesswork. *Business Week Magazine*.

Cates, C.U. et al. (2007, January 17). Use of virtual reality simulation for mission rehearsal for carotid stenting. *Journal of the American Medical Association*, 297(3), 265-266.

Chuang, T., Sung, W., & Lin, C. (2005, October). Application of a virtual reality-enhanced exercise protocol in patients after coronary bypass. *Archives Of Physical Medicine And Rehabilitation*, *86*(10), 1929-1932. Retrieved December 27, 2007, from MEDLINE database.

Chui, C., et al. (2006, December). Haptics in computer-mediated simulation: Training in vertebroplasty surgery. *Simulation and Gaming*, 37(4), 438-451.

Cohen, J., Cohen, S., Vora, K., Xue, X., Burdick, J., Bank, S., et al. (2006, September). Multicenter, randomized, controlled trial of virtual-reality simulator training in acquisition of competency in colonoscopy. *Gastrointestinal Endoscopy*, *64*(3), 361-368. Retrieved December 27, 2007, from MEDLINE database.

Cohen, L.T., Corrigan, J.M., and Donaldson, M.S. editors. (1999, November). *To err is human*. Washington D.C.: National Academy Press.

Cooke, M., Irby, D., Sullivan, W., & Ludmerer, K. (2006, September 28). American medical education 100 years after the Flexner report. *The New England Journal Of Medicine*, *355*(13), 1339-1344. Retrieved March 16, 2008, from MEDLINE database.

Dankelman, J., & Di Lorenzo, N. (2005). Editorial: Surgical training and simulation. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, Retrieved December 18, 2007, from MEDLINE database.

Dankelman, J., & Di Lorenzo, N. (2005). Surgical training and simulation. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, *14*(4), 211-213. Retrieved October 21, 2007, from MEDLINE database.

Dankelman, J., Chmarra, M., Verdaasdonk, E., Stassen, L., & Grimbergen, C. (2005). Fundamental aspects of learning minimally invasive surgical skills. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, *14*(4), 247-256. Retrieved December 18, 2007, from MEDLINE database.

Davis D, Thomson M, O'Brien M, et al. (1999) Impact of formal continuing medical education: do conferences, workshops, rounds and other traditional continuing education activities change physician behaviour or health care outcomes. *Journal of the American Medical Association*, 282, 867–74.

Davis D, Thomson M, Oxman A, Haynes R. (1995) Changing physician performance. A systematic review of the effect of continuing medical education strategies. *Journal of the American Medical Association*, 274, 700–5.

De Leo, G., Ponder, M., Molet, T., Fato, M., Thalmann, D., Magnenat-Thalmann, N., et al. (2003, June). A Virtual Reality System for the Training of Volunteers Involved in Health Emergency Situations. *CyberPsychology & Behavior, 6*(3), 267-274. Retrieved October 21, 2007, from Business Source Premier database.

Debas, H., Bass, B., Brennan, M., Flynn, T., Folse, J., Freischlag, J., et al. (2005, January). American Surgical Association Blue Ribbon Committee Report on Surgical Education: 2004. *Annals Of Surgery*, *241*(1), 1-8. Retrieved December 27, 2007, from MEDLINE database.

Denson JS, Abrahamson S. (1969). A Computer-controlled patient simulator. *Journal of the American Medical Association*, 208, 504–8.

Dunkin, B., Adrales, G., Apelgren, K., & Mellinger, J. (2007, March 16). Surgical simulation: a current review. *Surgical Endoscopy, 21*(3), 357-366. Retrieved December 27, 2007, from MEDLINE database.

Eversbusch, A., & Grantcharov, T. (2004, October 26). Learning curves and impact of psychomotor training on performance in simulated colonoscopy: a randomized trial using a virtual reality endoscopy trainer. *Surgical Endoscopy*, *18*(10), 1514-1518. Retrieved December 27, 2007, from MEDLINE database.

Flexner, A. (1910). *Medical education in the United States and Canada*. New York: Carnegie Foundation for the Advancement of Teaching. Accessed online March 10, 2008 at http://www.carnegiefoundation.org/elibrary/DOCS/flexner_report.pdf

Frezza, E., Solis, R., Silich, R., Spence, R., & Martin, M. (1999, September). Competency-based instruction to improve the surgical resident technique and accuracy of the trauma ultrasound. *The American Surgeon*, 65(9), 884-888. Retrieved March 24, 2008, from MEDLINE database.

Gaba, D. (1992, April). Improving anesthesiologists' performance by simulating reality. *Anesthesiology*, *76*(4), 491-494. Retrieved December 27, 2007, from MEDLINE database.

Garden, A., Robinson, B., Weller, J., Wilson, L., & Crone, D. (2002, March 22). Education to address medical error--a role for high fidelity patient simulation. *The New Zealand Medical Journal*, *115*(1150), 133-134. Retrieved December 27, 2007, from MEDLINE database.

Gerson, L., & Van Dam, J. (2003, July). A prospective randomized trial comparing a virtual reality simulator to bedside teaching for training in sigmoidoscopy. *Endoscopy*, *35*(7), 569-575. Retrieved December 27, 2007, from MEDLINE database.

Good, M. (2003, November). Patient simulation for training basic and advanced clinical skills. *Medical Education*, *37 Suppl 1,* 14-21. Retrieved October 21, 2007, from MEDLINE database.

Gordon, D., Issenberg, S., Gordon, M., LaCombe, D., McGaghie, W., & Petrusa, E. (2005, March). Stroke training of prehospital providers: an example of simulation-enhanced blended learning and evaluation. *Medical Teacher*, *27*(2), 114-121. Retrieved October 21, 2007, from MEDLINE database.

Haluck, R. (2005). Design considerations for computer-based surgical simulators. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, *14*(4), 235-243. Retrieved December 18, 2007, from MEDLINE database.

Halvorsen, F., Elle, O., & Fosse, E. (2005). Simulators in surgery. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, *14*(4), 214-223. Retrieved December 18, 2007, from MEDLINE database.

Hoffman, K. and Abrahamson, S. (1975, December). The Cost effectiveness of Sim One. *Journal of Medical Education*, 50, 1127-1128.

Holm, H. (1998, February 21). Quality issues in continuing medical education. *BMJ (Clinical Research Ed.)*, *316*(7131), 621-624. Retrieved December 27, 2007, from MEDLINE database.

Holtschneider, M.E. (2007, May). Better communication, better care through high-fidelity simulation. *Nursing Management*, 55-57.

Howard, S., Gaba, D., Fish, K., Yang, G., & Sarnquist, F. (1992, September). Anesthesia crisis resource management training: teaching anesthesiologists to handle critical incidents. *Aviation, Space, And Environmental Medicine*, *63*(9), 763-770. Retrieved December 27, 2007, from MEDLINE database.

Institute of Medicine (1999). *To err is human: Building a safer health system*. Washington, D.C.: National Academy Press.

Issenberg, S., McGaghie, W., Hart, I., Mayer, J., Felner, J., Petrusa, E., et al. (1999, September 1). Simulation technology for health care professional skills training and assessment. *JAMA: The Journal of The American Medical Association*, *282*(9), 861-866. Retrieved October 21, 2007, from MEDLINE database.

Issenburg, S.B. (2005). Features and uses of high-fidelity medical simulations that lead to effective learning: a BEME systematic review. *Medical Teacher*, 27(1), 10–28

Kastner, et al. (2004, August). *Carcass disposal: A Comprehensive review*. National Agricultural Biosecurity Center Consortium, Kansas State University.

Kaufman, M. and Stein, R. (2006, January 10). Record share of economy spent on health care. *Washington Post* newspaper.

Kneebone, R. (2003, March). Simulation in surgical training: educational issues and practical implications. *Medical Education*, *37*(3), 267-277. Retrieved October 21, 2007, from MEDLINE database.

Kneebone, R., & ApSimon, D. (2001, September). Surgical skills training: simulation and multimedia combined. *Medical Education*, 35(9), 909-915. Retrieved October 21, 2007, from MEDLINE database.

Kurrek M.M., Devitt J.H. (1997, November). The cost for construction and operation of a simulation centre. *Canadian Journal of Anesthesia*, 44(11), 1191–5.

Kyrkjebo, J.M., Brattebo, G., and Smith-Strom, H. (2006, October). Improving patient safety by using interprofessional simulation training in health professional education. *Journal of Interprofessional Care*, 20(5), 507-516.

Lasater, K. (2007, June). High-fidelity simulation and the development of clinical judgment: Students' experiences. *Journal of Nursing Education*, 46(6), 269-277.

LeBlang, T. (1997, Autumn). Use of a mock trial simulation to enhance legal medicine education for medical students. *Caduceus (Springfield, Ill.)*, *13*(2), 65-75. Retrieved December 27, 2007, from MEDLINE database.

Liaw, S., Pearce, C. and Keppell, M. (2002). Developing a web-based learning network for continuing medical education. *Journal of Workplace Learning*, 14(3), 98-108.

Mantovani, F., Castelnuovo, G., Gaggioli, A., & Riva, G. (2003, August). Virtual Reality Training for Health-Care Professionals. *CyberPsychology & Behavior*, 6(4), 389. Retrieved October 21, 2007, from Business Source Premier database.

Marshall, R., Smith, J., Gorman, P., Krummel, T., Haluck, R., & Cooney, R. (2001, July). Use of a human patient simulator in the development of resident trauma management skills. *The Journal Of Trauma*, *51*(1), 17-21. Retrieved April 13, 2008, from MEDLINE database.

Martin, M., Vashisht, B., Frezza, E., Ferone, T., Lopez, B., Pahuja, M., et al. (1998, August). Competency-based instruction in critical invasive skills improves both resident performance and patient safety. *Surgery*, 124(2), 313-317. Retrieved March 24, 2008, from MEDLINE database.

McDougall, E. (2007, March). Validation of surgical simulators. *Journal Of Endourology / Endourological Society*, 21(3), 244-247. Retrieved December 27, 2007, from MEDLINE database.

McGaghie, W., Issenberg, S., Petrusa, E., & Scalese, R. (2006, August). Effect of practice on standardised learning outcomes in simulation-based medical education. *Medical Education*, 40(8), 792-797. Retrieved October 21, 2007, from MEDLINE database.

Mullan, F. (2003, Jul/Aug). The future of medical education: A call for action. *Health Affairs*, 22(4), 88-96.

Murphy, J., Torsher, L., & Dunn, W. (2007, March). Simulation medicine in intensive care and coronary care education. *Journal Of Critical Care*, 22(1), 51-55. Retrieved December 27, 2007, from MEDLINE database.

Murray, D., Boulet, J., Kras, J., Woodhouse, J., Cox, T., & McAllister, J. (2004, November). Acute care skills in anesthesia practice: a simulation-based resident performance assessment. *Anesthesiology*, 101(5), 1084-1095. Retrieved December 28, 2007, from MEDLINE database.

Murray, D., Boulet, J., Ziv, A., Woodhouse, J., Kras, J., & McAllister, J. (2002, September). An acute care skills evaluation for graduating medical students: a pilot study using clinical simulation. *Medical Education*, 36(9), 833-841. Retrieved December 28, 2007, from MEDLINE database.

Mutter, D., Rubino, F., Temporal, M., & Marescaux, J. (2005). Surgical education and Internet-based simulation: The World Virtual University. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, 14(4), 267-274. Retrieved December 18, 2007, from MEDLINE database.

Nehring, W.M., Ellis, W.E., and Lashley, F.R. (2001, June). Human patient simulators in nursing education: An overview. *Simulation and Gaming*, 32(2), 194-204.

Norman, G., & Schmidt, H. (1992, September). The psychological basis of problem-based learning: a review of the evidence. *Academic Medicine: Journal Of The Association Of American Medical Colleges*, 67(9), 557-565. Retrieved April 13, 2008, from MEDLINE database.

Owen, H., & Plummer, J. (2002, July). Improving learning of a clinical skill: the first year's experience of teaching endotracheal intubation in a clinical simulation facility. *Medical Education*, 36(7), 635-642. Retrieved December 27, 2007, from MEDLINE database.

Patel, V. and Kaufman, D. (1995). Clinical reasoning and biomedical knowledge: implications for teaching. In J. Higgs and M. Jones (Eds), *Clinical reasoning in the health professions*. Boston, MA: Butterworth Heinemann.

Poss, R., Mabrey, J., Gillogly, S., Kasser, J., Sweeney, H., Zarins, B., et al. (2000, October). Development of a virtual reality arthroscopic knee simulator. *The Journal Of Bone And Joint Surgery. American Volume*, 82-A(10), 1495-1499. Retrieved December 27, 2007, from MEDLINE database.

Reznick, R. (1993, March). Teaching and testing technical skills. *American Journal Of Surgery*, 165(3), 358-361. Retrieved March 16, 2008, from MEDLINE database.

Reznick, R., Cohen, R., & Guest, C. (1990). The surgeon simulator. *Medical Teacher*, *12*(1), 63-68. Retrieved January 1, 2008, from MEDLINE database.

Reznick, R.K. and MacRae, H. (2006, December 21). Teaching surgical skills – changes in the wind. *New England Journal of Medicine*, 355(25), 2664-2669.

Rhyne, T. (2002, July). Computer games and scientific visualization. *Communications of the ACM*, 45(7), 41-44.

Riley R.H., Wilks D.H., & Freeman J.A. (1997). Anaesthetists attitudes towards an anaesthesia simulator. A comparative survey: U.S.A and Australia. *Anaesthetic Intensive Care*, 25, 514–519.

Ritter, M.E., & Bowyer, M. (2005). Simulation for trauma and combat casualty care. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, 14(4), 224-234. Retrieved December 18, 2007, from MEDLINE database.

Roach, M. (2003). *Stiff: The Curious lives of human cadavers*. New York: W.W. Norton.

Robb, R. (1997). Virtual endoscopy: evaluation using the visible human datasets and comparison with real endoscopy in patients. *Studies In Health Technology And Informatics*, 39, 195-206. Retrieved December 27, 2007, from MEDLINE database.

Rogers, D. (2002, December). Ethical and educational considerations in minimally invasive surgery training for practicing surgeons. *Seminars In Laparoscopic Surgery*, *9*(4), 206-211. Retrieved December 27, 2007, from MEDLINE database.

Rolfe, J.M. and Staples, K.J. (1986). *Flight Simulation*. Cambridge, UK: Cambridge University Press.

Rolfsson, G., Nordgren, A., Bindzau, S., Hagström, J., McLaughlin, J., & Thurfjell, L. (2002). Training and assessment of laparoscopic skills using a haptic simulator. *Studies In Health Technology And Informatics*, 85, 409-411. Retrieved December 27, 2007, from MEDLINE database.

Sarker, S., & Patel, B. (2007, December 19). Simulation and surgical training. *International Journal Of Clinical Practice*, 61(12), 2120-2125. Retrieved December 27, 2007, from MEDLINE database.

Satava, R. (1993, May). Virtual reality surgical simulator. The first steps. *Surgical Endoscopy*, 7(3), 203-205. Retrieved April 13, 2008, from MEDLINE database.

Satava, R. (2004a, May 19). Disruptive visions: surgical education. *Surgical Endoscopy*, 18(5), 779-781. Retrieved December 27, 2007, from MEDLINE database.

Satava, R. (2004b, September). Disruptive visions: predictive simulation--between scientific method and clinical trial is the role of modeling and simulation in scientific discovery and validation. *Surgical Endoscopy*, 18(9), 1297-1298. Retrieved December 27, 2007, from MEDLINE database.

Satava, R. (2005a). Identification and reduction of surgical error using simulation. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, 14(4), 257-261. Retrieved December 18, 2007, from MEDLINE database.

Satava, R. (2005b, March). Days 2 and 3 of the dawn of modern military surgery: the sequel to Senn. *Journal Of The American College Of Surgeons*, 200(3), 316-320. Retrieved December 27, 2007, from MEDLINE database.

Satava, R. (2005c, June). The scientific method is dead--long live the (new) scientific method. *Surgical Innovation*, 12(2), 173-176. Retrieved December 27, 2007, from MEDLINE database.

Satava, R. (2007, March). The future of surgical simulation and surgical robotics. *Bulletin Of The American College Of Surgeons*, 92(3), 13-19. Retrieved December 27, 2007, from MEDLINE database.

Satava, R., & Jones, S. (1997, Autumn). Medicine beyond the year 2000. *Caduceus (Springfield, Ill.)*, 13(2), 49-64. Retrieved December 27, 2007, from MEDLINE database.

Schijven, M., & Jakimowicz, J. (2005a). Validation of virtual reality simulators: Key to the successful integration of a novel teaching technology into minimal access surgery. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, 14(4), 244-246. Retrieved December 18, 2007, from MEDLINE database.

Schwind, H.A. (2001, June). Components of an effective medical simulation software solution. *Simulation and Gaming*, 32(2), 240-249.

Sedlack, R., Petersen, B., Binmoeller, K., & Kolars, J. (2003, June). A direct comparison of ERCP teaching models. *Gastrointestinal Endoscopy*, 57(7), 886-890. Retrieved April 6, 2008, from MEDLINE database.

Selder, A. (2006, September). Medical associations, medical education and training on the job. *CESifo Economic Studies*, 52(3), 548-565.

Seybert, A.L. et al. (2006, June 15). Pharmacy student response to patient-simulation mannequins to teach performance-based pharmacotherapeutics. *American Journal of Pharmaceutical Education*, 70(3), article 48.

Seymour, N. (2005). Integrating simulation into a busy residency program. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally*

Invasive Therapy, 14(4), 280-286. Retrieved December 18, 2007, from MEDLINE database.

Spencer, K.W. (2006, Oct-Dec). Patient simulation to enhance patient safety. *Plastic Surgical Nursing*, 26(4), 195-199.

Spitzer, V. (1997, Autumn). The visible human: a new language for communication in health care education. *Caduceus*, 13(2), 42-48. Retrieved December 27, 2007, from MEDLINE database.

Stafford, F. (2005, November). The significance of de-roling and debriefing in training medical students using simulation to train medical students. *Medical Education*, 39(11), 1083-1085. Retrieved October 21, 2007, from MEDLINE database.

Stimmel, B., Cohen, D., Fallar, R., & Smith, L. (2006, May). The use of standardised patients to assess clinical competence: does practice make perfect?. *Medical Education*, 40(5), 444-449. Retrieved January 1, 2008, from MEDLINE database.

Sutherland, L., Middleton, P., Anthony, A., Hamdorf, J., Cregan, P., Scott, D., et al. (2006, March). Surgical simulation: a systematic review. *Annals Of Surgery*, 243(3), 291-300. Retrieved December 27, 2007, from MEDLINE database.

Tabas, J.A. et al. (2005). A Comprehensive, unembalmed cadaver-based course in advanced emergency procedures for medical students. *Academic Emergency Medicine*, 12(8), 782-785.

Thacker, P.D. (2003, Oct 22-29). Fake worlds offer real medicine: Virtual reality finding a role in treatment and training. *Journal of the American Medical Association*, 290(16), 2107-2112.

Time Magazine. (1937, March 29). Cadavers. *Time Magazine*. Accessed online on April 2, 2008 at http://www.time.com/.

Tsai, M., Hsieh, M., & Jou, S. (2001, September). Virtual reality orthopedic surgery simulator. *Computers in Biology and Medicine*, 31(5), 333-351. Retrieved December 27, 2007, from MEDLINE database.

United States Census Bureau. (2001, April). *1997 Economic census: Health care and social assistance*. EC97S62S-SM. Washington D.C.: US.

Viciana-Abad, R., Reyes-Lecuona, A., García-Berdones, C., & Díaz-Estrella, A. (2004). A preliminary study of presence in virtual reality training simulation for medical emergencies. *Studies In Health Technology And Informatics*, 98, 394-396. Retrieved December 27, 2007, from MEDLINE database.

Wallace, P. (1997, Autumn). Following the threads of an innovation: the history of standardized patients in medical education. *Caduceus*, 13(2), 5-28. Retrieved December 27, 2007, from MEDLINE database.

Wantman, A., & Chin, C. (2003, November). Use of simulation in paediatric anaesthesia training. *Paediatric Anaesthesia*, 13(9), 749-753. Retrieved October 21, 2007, from MEDLINE database.

Waseda, M., Inaki, N., Mailaender, L., & Buess, G. (2005). An innovative trainer for surgical procedures using animal organs. *Minimally Invasive Therapy & Allied Technologies: MITAT: Official Journal Of The Society For Minimally Invasive Therapy*, 14(4), 262-266. Retrieved December 18, 2007, from MEDLINE database.

Wayne, D., Butter, J., Siddall, V., Fudala, M., Linquist, L., Feinglass, J., et al. (2005, Summer). Simulation-based training of internal medicine residents in advanced cardiac life support protocols: a randomized trial. *Teaching And Learning In Medicine*, 17(3), 210-216. Retrieved October 21, 2007, from MEDLINE database.

Weller, J., Dowell, A., Kljakovic, M., & Robinson, B. (2005, November). Simulation training for medical emergencies in general practice. *Medical Education*, 39(11), 1154-1154. Retrieved October 21, 2007, from MEDLINE database.

Weller, J., Wilson, L., & Robinson, B. (2003, May). Survey of change in practice following simulation-based training in crisis management. *Anaesthesia*, 58(5), 471-473. Retrieved October 21, 2007, from MEDLINE database.

Ziv, A., Ben-David, S., & Ziv, M. (2005, May). Simulation based medical education: an opportunity to learn from errors. *Medical Teacher*, 27(3), 193-199. Retrieved December 27, 2007, from MEDLINE database.

Ziv, A., Wolpe, P., Small, S., & Glick, S. (2003, August). Simulation-based medical education: an ethical imperative. *Academic Medicine: Journal Of The Association Of American Medical Colleges*, 78(8), 783-788. Retrieved December 27, 2007, from MEDLINE database.

Game Technology for Non-Entertainment Applications

Abt, C. (1970). *Serious Games*. New York: The Viking Press.

Aoyama, Y. and Izushi, H. (2003). Hardware gimmick or cultural innovation? Technological, cultural, and social foundations of the Japanese video game industry. *Research Policy*, 32, 423-444.

Beck, J.C. and Wade, M. (2004). *Got game: How the gamer generation is reshaping business forever*. Boston, MA: Harvard Business School Press.

Bergeron, B. (2006). *Developing serious games*. Charles River Media.

Bushnell, N. (1996, August). Relationships between fun and the computer business. *Communications of the ACM*, 39(8), 31-37.

Castronova, E. (2001). Virtual worlds: A First-hand account of market and society on the cyberian frontier. In The *Gruter institute working paper on law, economics, and evolutionary biology*. Retrieved June 22, 2006 from http://papers.ssrn.com/sol3/papers.cfm?abstract_id=294828#PaperDownload.

Chatham, R.E. (2007, July). Games for training. *Communications of the ACM*, 50(7), 37-43.

Connell, R. (1924). *The Most Dangerous Game*. Whitefish, MT: Kessinger Publishing

Demaria, R. and Wilson, J. (2004). *High Score: The Illustrated history of electronic games*. New York: McGraw-Hill Publishing.

Edmonds, R. (2007). *Virtual Worlds*. SRI Consulting Business Intelligence. Abstract available at http://www.sric-bi.com/Explorer/VW.shtml#viewpoints.

Federation of American Scientists. (2006a). *R&D challenges for games in learning*. Washington D.C.: Author.

Federation of American Scientists. (2006b). *Summit on educational games: Harnessing the power of video games for learning*. Washington D.C.: Author.

Ghamari-Tabrizi, S. (1995). The Worlds of Herman Kahn: The Intuitive science of thermonuclear war. Boston, MA: Harvard University Press.

Herz, J. and Macedonia, M. (2002, April). Computer games and the military: Two views. *Defense Horizons*, 11. Retrieved June 28, 2006 from http://www.ndu.edu/inss/DefHor/DH11/DH11.htm

Hutchison, J. (1997, November). The Junior Red Cross goes to Healthland. *American Journal of Public Health*, 87(11), 1816-1823.

Jana, R. (2008, March 3). The (Game) doctor is in. *Business Week Magazine*, p. 70.

Kelleher, C. and Pausch, R. (2007, July). Using storytelling to motivate programming. *Communications of the ACM*, 50(7), 59-64.

Kelly, H., et al. (2007, July). How to build serious games. *Communications of the ACM*, 50(7), 45-49.

Kushner, D. (2002, August). The wizardry of id. *IEEE Spectrum*, 39(8), 42-47.

Lane, D. (1995, May). On a Resurgence of management simulations and games. *Journal of the Operational Research Society*, 46(5), 604-625.

Lenoir, T. (2003). Programming theatres of war: Gamemakers as soldiers. In Latham, R. (Ed.) *Bombs and Bandwidth: The emerging relationship between information technology and security*. New York: The New Press. Retrieved January 14, 2006 from http://www.stanford.edu/dept/HPST/TimLenoir/Publications/Lenoir_TheatresOfWar.pdf

Maier, F. and Grobler, A. (2000, July). What are we talking about? – A Taxonomy of computer simulations to support learning. *System Dynamics Review*, 16(2), 135-148.

Mayo, M., Singer, M., and Kusumoto, K. (2005, December). Massively multiplayer environments for asymmetric warfare. *Proceedings of the 2005 Interservice/Industry Training, Simulation, and Education Conference*.

Mayo, M.J. (2007, July). Games for science and engineering education. *Communications of the ACM*, 50(7), 31-35.

Michael, D and Chen, S. (2005). *Serious games: Games that educate, train, and inform*. New York: Thompson Publishing.

Orbanes, P.E. (2004). *The Game makers: The Story of Parker Brothers*. Boston: Harvard Business School Press.

Putnam, R.D. (2001). *Bowling alone: The Collapse and revival of American community*. New York: Simon & Schuster.

Postigo, H. (2003). From Pong to Planet Quake: Post-industrial transitions from leisure to work. *Information, Communications, and Society*, 6(4), 593-607.

Prensky, M. (2001). *Digital game-based learning*. New York: McGraw Hill.

Prensky, M. (2006). *Don't bother me mom – I'm learning: How computer and video games are preparing your kids for 21st century success – and how you can help*. St. Paul, MN: Paragon House.

Rosen, L. and Weil, M. (1995, June). Adult and teenage use of consumer, business, and entertainment technology: Potholes on the information superhighway. *Journal of Consumer Affairs*, 29(5), 55-83.

Scacchi, W. (2004, Jan-Feb). Free and open source development practices in the game community. *IEEE Software*, 21(1), 59-66.

Schilling, M. (2003, Spring). Technological leapfrogging: Lessons from the U.S. video game console industry. *California Management Review*, 45(3), 6-32.

Shankar, V. and Bayus, B. (2003). Network effects and competition: An Empirical analysis of the home video game industry. *Strategic Management Journal*, 45(2), 387-398.

Sheff, D. (1999). *Game over: Press start to continue*. Wilton, CT: Cyber Active Publishing.

Smed, J., Kaukoranta, T., and Hakonen, H. (2002, April). A Review on networking and multiplayer computer games. Technical Paper TR454 from the Turku Centre for Computer Science, University of Turku, Finland. Retrieved July 2, 2006 from http://staff.cs.utu.fi/~jounsmed/papers/TR454.pdf

Smith, R. (2007, March-April). The Disruptive Potential of Game Technologies: Lessons Learned from its Impact on the Military Simulation Industry. *Research Technology Management*, 50(2), 57-64.

Squire, K. and Steinkuehler, C. (2007). Generating cyberculture/s: The Case of Star Wars Galaxies. In D. Gibbs and K.L. Krause (Eds.), *Cyberlines 2.0 languages and cultures of the Internet*. Albert Park, Australia: James Nicholas Publishers.

Steinkuehler, C. (2005a). The new third place: Massively multiplayer online gaming in American youth culture. *Tidskrift Journal of Research in Teacher Education*, 3, 17-32. Umea Universitet (Sweden).

Steinkuehler, C. (2007, January). Massively multilayer online video gaming as participation in a discourse. *Mind, Culture, and Activity*, 13(1), 38-52.

Venkatraman, N. and Lee, C. (2004, December). Preferential linkage and network evolution: A Conceptual model and empirical test in the U.S. video game sector. *Academy of Management Journal*, 47(6), 876-2005.

Zyda, M. (2007, July). Creating a science of games. *Communications of the ACM*, 50(7), 27-29.

Zyda, M., et.al. (2003, December). This year in the MOVES institute. *Proceedings of the Second International Conference on Cyberworlds*. xxxii.

Zyda, M. (2005, September). From visual simulation to virtual reality to games. *IEEE Computer*, 38(9), 30-34.

Dissertations on Computer Games

Clearwater, David A. (2006). Full spectrum propaganda: The United States military, video games, and the genre of the military-themed shooter. Ph.D. dissertation, McGill University (Canada), Canada. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT NR25119).

Garrelts, Nathan Clinton. (2003). The official strategy guide for video game studies: A grammar and rhetoric of video games. Ph.D. dissertation, Michigan State University, United States -- Michigan. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3100425).

Nair, Harikesh Sasikumar, (2005). Intertemporal price discrimination in the United States market for 32-bit video games. Ph.D. dissertation, The University of Chicago, United States -- Illinois. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3195046).

Nichols, Randall James. (2005). The games people play: A political economic analysis of video games and their production. Ph.D. dissertation, University of Oregon, United States --

Oregon. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3201695).

O'Connor, Thomas Joseph. (2001). Investigating exercise for manual wheelchair users with and without video game play using the GAME(Wheels) System. Ph.D. dissertation, University of Pittsburgh, United States -- Pennsylvania. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3013318).

Robison, Alice J. (2006). Inventing fun: Videogame design as a writing process. Ph.D. dissertation, The University of Wisconsin - Madison, United States -- Wisconsin. Retrieved September 9, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3234639).

Steinkuehler, Constance A. (2005b). Cognition and learning in massively multiplayer online games: A critical approach. Ph.D. dissertation, The University of Wisconsin - Madison, United States -- Wisconsin. Retrieved September 9, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3186279).

Vaupel, Christine Angela. (2002). The effects of video game playing on academic task performance and brain wave activity. Ph.D. dissertation, The University of Tennessee, United States -- Tennessee. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3054150).

Wainess, Richard Allen. (2006). The effect of navigation maps on problem solving tasks instantiated in a computer-based video game. Ph.D. dissertation, University of Southern California, United States -- California. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3237181).

Whitlock, Katherine Lynne. (2004). Theatre and the video game: Beauty and the beast. Ph.D. dissertation, The Ohio State University, United States -- Ohio. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3148412).

Williams, Dmitri C. (2004). Trouble in River City: The social life of video games. Ph.D. dissertation, University of Michigan, United States -- Michigan. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3122072).

Yu, Yi-Lin. (2004). The impact of perceived interactivity and vividness of video games on customer buying behavior. Ph.D. dissertation, Lynn University, United States -- Florida. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT 3123912).

Zaparyniuk, Nicholas Eugene. (2006). The exploration of video games as a tool for problem solving and cognitive skills development. M.Ed. dissertation, University of Alberta (Canada), Canada. Retrieved September 2, 2007, from ProQuest Digital Dissertations database. (Publication No. AAT MR13765).

Simulation

Casti, J. (1997). Would-be Worlds: How simulation is changing the frontiers of science. New York: John Wiley & Sons.

Dodsworth, C. (Ed.). (1998). *Digital illusion: Entertaining the future with high technology*. New York: ACM Press.

Elmaghraby, S.E. (1968, June). The role of modeling in IE design. *Industrial Engineering*, 6, 292-305.

Lane, J.L., Slavin, S., and Ziv, A. (2001, September). Simulation in medical education: A review. *Simulation and Gaming*, 32(3), 297-314.

Miller, D.C. and Thorpe, J.A. (1995, August). SIMNET: The Advent of Simulator Networking. *Proceedings of the IEEE*. 83(8), 1114-1123.

National Research Council. (1997). *Modeling and simulation: Linking entertainment and defense*. Washington DC: National Academies Press.

National Research Council. (2006). *Defense modeling, simulation, and analysis*. Washington D.C.: National Academies Press.

Perla, P. (1990). *The Art of wargaming*. Annapolis, MD: Naval Academy Press.

Schrage, M. (2000). *Serious play: How the world's best companies simulate to innovate*. Boston: Harvard Business School Press.

History of Technology

Boot, M. (2006). *War made new: Technology, warfare, and the course of history, 1500 to today*. New York: Penguin Books.

Cardwell, D.S.L. (1972). *Turning points in western technology*. Canton, MA: Science History Publications.

Cardwell, D. (1995). *The Norton history of technology*. New York: WW Norton and Company.

Carlson, R. and Goldman, B. (1994). *Fast forward: Where technology, demographics, and history will take America and the world in the next 30 years*. New York: Harper Business.

Klemm, F. (1991). *A History of western technology*. Ames, Iowa: Iowa State University Press.

McClellan, J.E. and Dorn, H. (1999). *Science and technology in world history: An Introduction*. Baltimore, MD: Johns Hopkins University Press.

Pursell, C. (1995). *The Machine in America: A Social history of technology*. Baltimore, MD: Johns Hopkins University Press.

Pursell, C.W. (1981). *Technology in America: A History of individuals and ideas*. Cambridge, MA: MIT Press.

Solow, R. (1957, August). Technical change and the aggregate production function. *Review of Economics and Statistics*, 39(3), 312-320.

Tapscott, D. (1998). *Growing up digital: The Rise of the net generation*. New York: McGraw-Hill.

Tapscott, D. and Williams, A.D. (2006). *Wikinomics: How mass collaboration changes everything*. New York: Portfolio Books.

Disruptive Innovation and Creative Destruction

Chesbrough, H. (2003). *Open innovation: The New imperative for creating and profiting from technology*. Boston, MA: Harvard Business School Press.

Christensen, C. (1997). *The Innovator's dilemma: When new technologies cause great firms to fail*. Boston, MA: Harvard Business School Press.

Hargadon, A. (2003). *How breakthroughs happen: The Surprising truth about how companies innovate*. Boston, MA: Harvard Business School Press.

Hart, S.L. and Milstein, M.B. (1999, Fall). Global sustainability and the creative destruction of industries. *Sloan Management Review*, 41(1), 23-33.

Kuhn, T.S. (1970). *The Structure of scientific revolutions, 2nd edition*. Chicago: University of Chicago Press.

Leonard, D. (1995). *Wellsprings of Knowledge: Building and sustaining the sources of innovation*. Boston, MA: Harvard Business School Press.

Perelman, M. (1995, Summer). Retrospectives: Schumpeter, David Wells, and Creative Destruction. *Journal of Economic Perspectives*, 9(3), 189-197.

Reinganum, J.F. (1985, February). Innovation and industry evolution. *The Quarterly Journal of Economics*, 100(1), 81-99.

Rogers, E.M. (1995). *Diffusion of innovations, fourth edition*. New York: Free Press.

Schumpeter, J.A. (1976). *Capitalism, Socialism, and Democracy*. New York: Harper & Row Publishers.

Smith, K.G., Ferner, W.J., and Grimm, C.M. (2001, May). King of the hill: Dethroning the industry leader. *Academy of Management Executive*, 15(2), 59-70.

von Hippel, E. (2005). *Democratizing innovation*. Boston, MA: MIT Press.

Wells, D. A. (1889). *Recent economic changes and their effect on the production and distribution of wealth and the well-being of society*. New York: D. Appleton and Company. Accessed online at http://books.google.com/.