

Simulated vs. Hands-on Laboratory Position Paper

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Abstract

Virtual reality software has evolved to create ever more realistic virtual environments. Sophisticated virtual education laboratory experiments are now possible. Some educators and researchers question the value of hands-on laboratories relative to virtual laboratories. Researchers have investigated students' acceptance of virtual laboratories and the relative effectiveness of virtual laboratories compared to traditional hands-on laboratories. Research results indicated that students' attitudes toward virtual laboratory experiments are positive, and researchers found virtual laboratory experiments to be as effective as or more effective than traditional hands-on laboratories. However, researchers have not measured simulated laboratory effectiveness for all standard education laboratory goals. Simulated laboratory technology will be part of science education, but how to introduce laboratory simulations and the appropriate role for simulated laboratories remains a subject of debate. Are virtual laboratory experiments acceptable substitutes for hands-on laboratories in secondary education? To explore this question, laboratory goals and effectiveness criteria must be defined and measured for secondary education. This paper explores the goals and effectiveness of virtual and hands-on education laboratories. This paper also outlines the arguments for and against the replacement of traditional hands-on labs with simulated laboratories in secondary science education and makes a case for using laboratory simulations to supplement rather than replace traditional hands-on laboratories.

Keywords: hands-on laboratories, simulated laboratories, virtual laboratories

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Introduction

Chemical workers are required to perform analytical functions as part of their job. Laboratory functions performed by operators include, sample preparation, Karl Fischer titration, pH titration, gas chromatography, and color measurement. Chemical workers also must understand chemistry fundamentals to safely and responsibly follow and control chemical processes. Most new employees and some experienced employees do not have the basic math and chemistry education needed to succeed in a modern chemical plant, so basic chemistry and laboratory education is an essential part of employee training. Providing this training is a requirement of the OSHA PSM standard, and perhaps the most important part of my current work. Simulated laboratory exercises could be a cost effective and accessible way to both teach needed

laboratory skills and reinforce basic chemistry and process control concepts. However, simulated laboratory exercises would not be a wise use of the operators' time or company resources unless the net effectiveness was comparable to the hands-on training currently provided by me and other chemical engineers. Distributed Control Systems (DCS) monitor and control most operations in a modern chemical plant, and operators currently use DCS simulations as part of their education. DCS simulations are a type of virtual laboratory (Cardoso, Viera, & Gil, 2012), so virtual laboratories are already part of employee education. Researching the relative effectiveness of virtual laboratories versus hands-on laboratories will help me decide if the time and resources needed to implement more simulated laboratory employee training is worthwhile.

Historically hands-on laboratories were a part of high school chemistry courses. Hands-on laboratories help students learn laboratory skills, reinforce basic scientific concepts, allow open-ended inquires, and improve collaboration skills (Ma & Nickerson, 2006). Hands-on laboratories also help students become comfortable working safely with chemicals, scientific equipment, and specimens. However, hands-on laboratories are expensive to build and maintain (Crandall et al., 2015; Ma & Nickerson, 2006). Hands-on laboratories are also not as accessible to some students with special needs as simulated laboratories.

The extent to which simulated laboratories replace hands-on laboratories will likely be decided at the school district level rather than by individual instructors, but understanding the relative strengths of the two is still important to science instructors. Researching the relative effectiveness of virtual laboratories versus hands-on laboratories will help me learn the strengths and shortcomings of virtual laboratory exercises.

Hands-on laboratory lessons have been a traditional part of high school science education for decades (Singer, Hilton, & Schweingruber, 2006; National Research Council, 2005), and the value of hands-on laboratory lessons is generally acknowledged (Singer et al., 2006). Unfortunately, traditional hands-on laboratories are expensive to build, maintain, and staff (Ma & Nickerson, 2006). Some valuable laboratory lessons are not explored in traditional hands-on laboratories because the experiments would be too costly or too dangerous (Singer et al., 2006). Laboratory simulations are modern alternatives to traditional hands-on laboratories that could reduce the cost of laboratory education and make laboratory experiments more accessible.

Simulated and remote laboratories offer distance learners laboratory experiences that would be otherwise unavailable and allow on-campus students scheduling flexibility. Simulated laboratories can also allow students to explore in ways that would be unsafe or logistically impractical in physical laboratories. Simulated laboratories can also use animations to illustrate normally invisible processes such as the flow of electricity through a wire, and such illustrations may improve content knowledge learning (De Jong, Linn & Zacharia, 2013; Singer et al., 2006). The use of simulated laboratory lessons as supplements to traditional hands-on laboratory lessons is generally accepted. Several studies have found that simulated laboratory experiments were as effective as or more effective than traditional hands-on laboratory experiments. On the other hand, some professional scientific and education organizations have taken official positions that oppose the use of laboratory simulations as substitutes for hands-on laboratories. Simulated laboratory experiments could be cost effective and time saving alternatives to traditional hands-on laboratory

experiments in secondary education. The use of simulated laboratory experiments as substitutes for hands-on laboratory experiments is a subject of debate (Brinson, 2015).

Literature Review

In recent years several studies of the effectiveness of simulated laboratories compared to hands-on laboratories for science education were published. Three literature reviews of studies comparing the effectiveness of nontraditional laboratories and traditional hands-on laboratories have been published. The College Board, the National Science Teachers Association, National Research Council, and the American Chemical Society have published positions that oppose the use of simulated laboratory instruction in place of hands-on laboratory instruction (ACS, n.d.; College Board, n.d.; NSTA, n.d. Singer et al., 2006). The appropriate role for simulated laboratory lessons in education is a subject of current research and interest.

Are simulated laboratories acceptable substitutes for hands-on laboratories for secondary science education? To answer this question, simulated laboratories must be defined and the purpose of high school laboratories must be defined. A simulated lab is a computer-generated replica of a real laboratory experience (De Jong et al., 2013; Ma & Nickerson, 2006). Different researchers do not always measure laboratory effectiveness against the same set of goals (Brinson, 2015; Ma & Nickerson, 2006), but the National Research Council has identified seven standard laboratory goals which are discussed below (Singer et al., 2006). The effectiveness of a laboratory format is measured by demonstrated progress toward each of these goals. If simulated laboratories are acceptable substitutes for traditional hands-on laboratories, simulated laboratories must achieve essentially equal or better educational results for each laboratory goal. This paper explores arguments for and against the use of simulated laboratories as substitutes for traditional hands-on laboratories.

Professional Organizations Positions

The National Research Council investigated American high school science education laboratories and their findings are reported in the *America's Lab Report: Investigations in High School Science* (Singer et al., 2006). It was noted that the goals of laboratory lessons are not all ways clear and generally agreed upon. Singer et al., (2006, p. 3) stated that the goals of laboratory lessons should be “enhancing mastery of subject matter, developing scientific reasoning, understanding the complexity and ambiguity of empirical work, developing practical skills, understanding the nature of science, cultivating interest in science and interest in learning science, and developing teamwork abilities”. They acknowledged that computer simulations can allow investigations that would normally be impossible because of cost, safety concerns, or inaccessibility, and that simulations can make learning abstract concepts easier by making visual representations of processes that would be unseen in the real world. However, the report recommends that computer simulations supplement rather than replace hands-on laboratory lessons.

National Science Teachers Association developed the position statement *The Integral Role of Laboratory Investigations in Science Instruction* (National Science Teachers Association [NSTA], n.d.). The NSTA (n.d.) asserts that laboratory investigations are a necessary part of education at all grade levels and for all students. Laboratory lessons should have a clearly communicated educational purpose, encourage scientific content learning, encourage reflection,

encourage student discussion, and teach safe appropriate laboratory habits (NSTA, n.d.). Inquiry based laboratory lessons should be integrated into comprehensive unit lesson plans (NSTA, n.d.). High school students should have several opportunities per week to learn through laboratory explorations. High school laboratory lessons should afford students the opportunity to experience the uncertainty and variability of laboratory experiments, to calibrate analytical equipment, and to solve unexpected problems. Laboratory education should be supported with adequate facilities and budgets to make hands-on laboratory lessons possible. Scientific simulations are valuable tools, but not replacements for hands-on laboratory experience.

The American Chemical Society issued the public policy statement *Importance of Hands-on Laboratory Science* (American Chemical Society [ACS], n.d.). The ACS (n.d.) stated that learning through laboratory experience should be part of education at all grade levels. Laboratory education encourages critical thinking and problem solving skills (ACS, n.d.). Students gain important experience with laboratory equipment, with laboratory processes, and with reactants in hands-on laboratories. In hands-on laboratories students learn to safely and responsibly use chemicals and laboratory equipment through direct investigations. Continued investment in hands-on laboratory facilities is needed, and hands-on laboratories are necessary for chemistry education and to prepare students for technology careers. Computer simulations are useful teaching tools that may help reduce education costs, reduce hazardous waste generation, and improve laboratory safety, but computers are not adequate replacement for hands-on laboratory experiences. According to ACS (n.d., page 1), “The Society believes that there is no equivalent substitute for hands-on activities where materials and equipment are used safely and student experiences are guided.”

The College Board develops the course descriptions and standards for advanced placement courses in secondary education. *The AP Chemistry Course and Exam Description* states that 25% of instruction time should be allotted to hands-on laboratory experiments (College Board, n.d.). Course requirements include 16 or more hands-on investigations including six or more hands-on guided inquiry laboratory investigations (College Board, n.d.). The course description also says that students should be supported to generate investigation ideas, determine relevant variables, analyze data, and draw conclusions from hands-on laboratory investigations.

Standards

Laboratory education is a part of local, state, and national education standards. The Shelby County School district requires three science course credits including the *Lab Science Course* to graduate high school (Graduation Requirements, - Shelby County Schools, n.d.). The state of Tennessee also requires three science credits including one or more laboratory science courses to graduate high school (Graduation Requirements, n.d.). Tennessee *Chemistry I* standard states that students should be able to design experiments, understand and conduct laboratory procedures, correctly use chemistry lab equipment, and analyze scientific investigation results (Chemistry I, n.d.). Tennessee *Earth Science* standard states that students should be able to gather accurate qualitative and quantitative data using the appropriate instruments and be able to use data to reach valid conclusions (Earth Science, n.d.). Tennessee *Physics* standard and *Biology I* standard assert that students should be able to design investigations and compare their experimental results against the results of other investigators (Biology I, n.d.; Physics, n.d.). According to the NSTA, laboratory investigations support inquiry based learning and should be part of an integrated

education plan (NSTA, n.d.). Local, state, and national standards affirm the importance of laboratory investigations to teach practical laboratory skills, develop analytical skills, and develop scientific reasoning skills.

Educational Theories

Laboratory education is supported by the constructivist theory (Shiland, 1999). During laboratory investigations, students gather data and experience new phenomena that may reinforce their current schema or maybe in conflict with their current schema (Shiland, 1999). Students learn by integrating new laboratory evidence into their current understanding or by abandoning ideas that cannot be reconciled with new laboratory evidence (Shiland, 1999). Students learn from each other as well as from the instructor (Shiland, 1999). Students often work in pairs or groups in traditional hands-on laboratories which promotes leaning though collaboration. Collaboration skills are emphasized more in hands-on laboratories than in simulated laboratories (Ma & Nickerson, 2006). Learning through problem solving is a key part of the constructivist theory and a key part of laboratory lessons (Shiland, 1999). In both hands-on and simulated education laboratories, students modify and build on current ideas to create new ideas though active leaning and by problem solving which is constant with the constructivist theory of learning.

The VARK model identifies four sensory modalities involved in learning. (Abdulwahed & Nagy, 2009; Fleming & Baume, 2006). The modalities are visual, aural, read/write, and kinesthetic (Abdulwahed & Nagy, 2009; Fleming & Baume, 2006). Traditional hands-on laboratories support leaning for visual learners, aural learners, read/write learners, and kinesthetic learners. All the senses are utilized in a traditional hands-on laboratory. Charts, graphs and diagrams are used and created in traditional hand-on laboratories, so visual learners are supported. Laboratory discussions and collaborations support auditory learners. Written laboratory instructions and student generated lab reports are beneficial for read/write learners, and physical manipulation of lab components is beneficial for kinesthetic learners. Traditional hands-on laboratories support visual, aural, read/write, and kinesthetic sensory modalities.

Simulated laboratory lessons may be more beneficial for visual learners since simulations may add animations that highlight normally invisible processes (De Jong et al., 2013). Simulated laboratories may also include built-in data representations and charts that may benefit visual learners (De Jong et al., 2013). However, simulated laboratories do not benefit kinesthetic learners since there is no physical interaction with laboratory components. Simulated laboratories may or may not include realistic auditory effects and the opportunity to physically communicate with classmates, so simulated laboratories do not necessarily support auditory learners. Simulated laboratories support some but not all of the sensory modalities involved in learning identified in the VARK model.

Best Practices

Ma and Nickerson (2006) produced a literature review of remote, simulated, and hands-on laboratory studies. Four studies were reviewed that directly compared the effectiveness of hands-on to remote laboratories and found remote laboratories were equally effective. Two studies were reviewed that directly compared the effectiveness of hands-on laboratories to simulated laboratories. Hands-on laboratories were found to be superior to simulated laboratories in both studies. Three studies of mixed laboratory formats found good student acceptance of hybrid

laboratory formats. Ma and Nickerson (2006) also noted continuing debate about the relative effectiveness of each laboratory format and noted that laboratory goals and success criteria were not consistent between studies. Ma and Nickerson (2006) analyzed the measurement criteria used in 60 studies. Twenty studies for each laboratory format were categorized based on four laboratory lesson goals. Studies in all laboratory formats emphasized improved content knowledge and improved professional skills as goals (Ma & Nickerson, 2006). Problem solving and investigation skills were important in hands-on and simulated laboratory studies but not remote laboratory studies (Ma & Nickerson, 2006). Improving collaboration skills was important in 40% hands-on laboratory studies, 25% of simulation laboratory studies and 23% of remote laboratory studies (Ma & Nickerson, 2006). Ma and Nickerson (2006) concluded that disagreements about the relative effectiveness of different laboratory formats are at least partially caused by the lack of consistent education goals for education laboratories.

De Jong, Linn and Zacharia (2013) reviewed a selection of literature to compare virtual and physical laboratory merits. De Jong et al. (2013) point out that the use of simulated laboratories as replacements for hands-on laboratories is not universally accepted. De Jong et al. (2013) stated that physical and simulated laboratories can meet most laboratory education goals, but physical laboratories are more advantageous for developing practical laboratory skills and provide tactile information not provided by simulations. De Jong et al. (2013) stated that virtual laboratories are equivalent or superior replacements for hands-on laboratories for teaching conceptual understanding for all but very young students. De Jong et al. (2013) noted that simulated laboratories may be superior to hands-on laboratories at teaching content knowledge because simulations can provide an experiment lessons with fewer distracting details and can visually represent normally invisible phenomena. However, De Jong et al. (2013) pointed out that most studies that compare simulated and hands-on laboratory experiments base effectiveness on content knowledge improvement rather than the full range of laboratory education goals. De Jong et al. (2013) concluded that simulated laboratory experiments are acceptable substitutes for some but not all hands-on laboratory experiments and simulated experiments should be used when physical experiments are impractical or when simulated experiments are more effective.

Brinson (2015) reviewed recent studies of the relative effectiveness of traditional hands-on laboratories versus nontraditional laboratories. Brinson (2015) considered remote and simulated laboratories to be nontraditional. Brinson (2015) reviewed and analyzed 56 articles published after 2005 that directly compared the effectiveness of traditional and nontraditional laboratories. Brinson (2015, p 223) used the criteria of “knowledge and understanding, inquiry skills, practical skills, perception, analytical skills, and social and scientific communication” to analyze the laboratory goals of each study.

Brinson (2015) like De Jong et al. (2013) and Ma and Nickerson (2006) found almost all studies assessed content knowledge improvement. Even though inquiry based experimentation is explicitly recommended by NSTA (n.d.), inquiry skills were measure in only 7% of the studies (Brinson, 2015). Practical skills were assessed in 16% of the studies (Brinson, 2015). Improvement of students’ perception of science was measured by 53% of studies (Brinson, 2015). Analytical and social skills were measured in 15% and 9% of studies respectively (Brinson, 2015). Brinson (2015) like Ma and Nickerson (2006) found educators have not reached a consensus on

the goals of laboratory education, and this contributes to the debate about the relative effectiveness of different laboratory formats.

Brinson (2015) determined that 87% of studies found nontraditional laboratories to be equal to or superior to traditional laboratories at content knowledge improvement, and all studies that measured inquiry skills found nontraditional laboratories to be equal to or superior to hands-on laboratories. Brinson (2015) found that 78% of studies that assessed practical skills demonstrated that nontraditional laboratories were equal or superior to traditional laboratories. It should be noted that most studies that measure practical skills were studies of engineering laboratories rather than science laboratories. Nontraditional laboratories were found to be equal or superior to traditional laboratories in the 86% of studies that assessed perception, 87% of studies that assessed analytical skills, and 80% of studies that assessed social and scientific communication (Brinson, 2015). The majority of assessments used in the studies were exams and surveys (Brinson, 2015). Written reports, observations and practical assessments were the least used assessment tools in the studies (Brinson, 2015). Brinson (2015) noted that studies that indicated nontraditional laboratories are superior were more likely to rely on examination assessment tools, but studies that indicate traditional laboratories are superior were more likely to use surveys as assessment tools (Brinson, 2015). Brinson (2015) concluded that the recent studies indicate that nontraditional laboratories can achieve all laboratory goals as well as or better than traditional laboratories, but noted again that there is not a clear consensus on the goals of laboratory education.

Virtual Versus Hands-on Laboratory

Six recent articles are reviewed below that document studies that compare virtual and hands-on education science laboratories at grade levels ranging from junior high school through undergraduate. Because virtual reality is evolving, only articles published between 2007 and 2016 are reviewed here. Studies that compare the effectiveness of engineering laboratory formats are excluded from this review since those studies are not directly related to secondary science laboratories.

Yang and Heh (2007) investigated the effectiveness of traditional and virtual laboratories for teaching high school physics. Content knowledge improvement was measured using pre and post examinations. The exam reliability was analyzed and found to be reliable with a Cronbach Alpha score of 0.73. Process skills were assessed using the Science Process Skills Test (SPST). The SPST was deemed reliable with a Cronbach Alpha score of 0.86. Students' attitudes toward computers were measured using the Computer Attitude Scale that was deemed reliable with a Cronbach Alpha score of 0.88. One-hundred fifty 10th grade students (57% male, 43% female) were equally divided into treatment and control groups. The treatment group conducted four virtual laboratory physics experiments and the control group conducted four similar hands-on physics experiments. Participants in the treatment group used virtual rulers and protractors and other virtual tools to complete the experiments, and participants in the control group used similar physical measurement tools. The results were statistically significant, and the group conducting virtual laboratory experiments scored significantly higher than the control group in all categories measured (Yang & Heh 2007). Yang and Heh (2007) stated that virtual laboratory simulations are tools that should be used to improve student achievement.

Tatli and Ayas (2011) investigated the effectiveness of virtual laboratories for teaching 9th grade chemistry. Content knowledge improvement was measured with the Chemical-Changes Unit Achievement (CCUA) test before and after the laboratory lesson. CCUA reliability was analyzed and found to be reliable with a Spearman Brown reliability coefficient of score 0.85. Students' ability to identify laboratory equipment was also tested. Ninety 9th grade chemistry students were randomly assigned to a treatment group or to one of two control groups. Twenty students were in each group. Participants conducted a hands-on or virtual Chemical Changes Unit laboratory experiment. Post CCUA scores were significantly better for all groups indicating both laboratory formats effectively improved content knowledge (Tatli & Ayas, 2011). There was not a statistically significant difference in content knowledge improvement between the two control groups and the group that used a simulated laboratory (Tatli & Ayas, 2011). Pre and post scores for the laboratory equipment identification test were conflicting since one control group and the treatment group improved and the other control group made no improvement in equipment identification (Tatli & Ayas, 2011). Tatli and Ayas (2011) stated that this study suggested that virtual laboratories can be as effective as hands-on laboratories.

Pyatt and Sims (2012) investigated hands-on and virtual laboratory experiments used in a high school chemistry course. Pyatt and Sims (2012) assessed conceptual learning and student attitude in this investigation. Virtual and physical formats were used for two inquiry based laboratory experiments. The experiments were conducted over a two year period. The study included 96 participants in the first year and 88 students in the 2nd year. Participants in each year were assigned to one of two groups. A crossover design was used so that the control group for one experiment was the treatment group for the other experiment. Five new scales were developed for this study with a Cronbach Alpha score range of 0.72 to 0.90 and were deemed to be reliable. The scales used were Usefulness of Computers (UC), Anxiety Towards Computers (AC), Usefulness of Lab (UL), Open-endedness of Lab (OE), and Equipment Usability (EU). The scales were used to create a new survey, Virtual and Physical Experimentation Questionnaire (VPEQ). No statistically significant difference was found between conceptual learning with virtual experiments and hands-on experiments (Pyatt & Sims, 2012). Data collection was faster in the virtual laboratories (Pyatt & Sims, 2012). Student laboratory performance with both laboratory formats was equivalent (Pyatt & Sims, 2012). Students' attitude toward use of computers and simulations in the laboratory was positive (Pyatt & Sims, 2012). Students felt that the simulated laboratory experiment was realistic and challenging, and the simulation was more open-ended (Pyatt & Sims, 2012). Pyatt and Sims (2012) conclude that virtual laboratory experiments may be acceptable alternatives to hands-on laboratory experiments.

Renken and Nunez (2013) investigated the use of virtual laboratories for teaching 7th grade physics. Students conducted two simple pendulum motions experiments that relate to Newton's laws of motion. Students could alter the pendulum length and the mass of the bob at the end of the pendulum. Participants in the physical laboratory had fewer variable options than participants in the virtual laboratory since a limited variety of physical weights and strings were provided for the physical experiment. Experiments could be performed in either a hands-on format or a virtual format. Experiments were recorded, and students could replay the experiments at normal or slow motion speed for both formats. Experiment recordings were also use to determine the experiment quality based on the control of variables and the number of experiment trials. Experiments were judged to be inadequate, adequate, or superior. One-hundred forty-seven 7th grade students were

randomly assigned to one of four groups. The groups were hands-on with real time replay, hands-on with slow motion replay, simulated with real-time replay, or simulated with slow motion replay. Students' conceptual knowledge was measured with a series of questions. Students were tested before the experiments, immediately after the experiments, and after 12 weeks. There was no statistically significant difference in conceptual understanding between groups who had access to real time and slow motion replay even though slow motion relay could have facilitated more accurate observations (Renken & Nunez, 2013). There was no statistically significant difference in conceptual understanding between the groups who conducted hands-on and simulated experiments (Renken & Nunez, 2013). Students who conducted experiments that were judged to be inadequate scored significantly lower than students who conducted experiments that were judged to be adequate or superior (Renken & Nunez, 2013). However, adequate not superior experiments were correlated with the highest scores (Renken & Nunez, 2013). Renken and Nunez (2013) speculated that this may be because repeated experiment trials may not be beneficial but were included in the experiment quality rating. Renken and Nunez (2013) concluded that a high quality experiment improves conceptual understanding regardless of the experiment format, and enhanced observation tools do not necessarily improve content learning. Renken and Nunez (2013) also recommend using simulations with caution since the wider degrees of freedom that this simulation provided may have encouraged more experiment trials but with poorer variable control.

Hawkins and Phelps (2013) investigated the effectiveness of traditional and virtual laboratories for teaching electrochemistry. Content knowledge improvement was measured using pre and post examinations. The exam reliability was analyzed and found to be reliable with a Cronbach Alpha score > 0.9 . Students were also asked to set up a physical salt bridge test apparatus to measure practical laboratory skills. A total of 169 undergraduate General Chemistry II students agreed to participate in the study. Eighty-four students were in the treatment group and used a simulated laboratory, and 79 students were in the control group and used a physical laboratory. Participants in both groups conducted a Daniell cell electrochemistry experiment. There was a statistically significant difference between pre and post exam scores for both groups indicating that both gained content knowledge through experimentation (Hawkins & Phelps, 2013). There was not a statistically significant difference in content knowledge improvement between the two groups (Hawkins & Phelps, 2013). Scores for the practical skills test were also not significantly different (Hawkins & Phelps, 2013). Hawkins and Phelps (2013) concluded that virtual laboratories were equivalent to physical laboratories for teaching students electrochemistry concepts and voltaic cell set-up. Hawkins and Phelps (2013) did not conclude that simulated laboratories are equivalent in all situations, but noted that more research is needed to determine when the use of virtual laboratories is advantageous.

Winkelmann, Scott, and Wong (2014) investigated high school student performance using a virtual chemistry laboratory built on the Second Life platform. Second Life is a popular multiuser online 3D virtual world. Students registered with Second Life and created avatars then conducted simulated kinetics experiments similar to the normal course hands-on kinetics experiments. Students completed lab reports, and a rubric was used to score lab reports and measure student achievement. An attitude survey was used to measure students' opinions. Five 11th grade students performed the virtual experiment and wrote lab reports. Four of these students agreed to share their lab report scores from the virtual experiment and their scores from other

hands-on experiment lab reports. The scores for both types of lab reports were high and there was no statistical difference with a 95% confidence level (Winkelmann et al., 2014). Students were accepting of the virtual laboratory format and did not have a preference for one format over the other. Winkelmann et al., (2014) noted that the Second Life environment allowed a realistic detailed copy of real laboratory environments. Winkelmann et al., (2014) concluded that virtual laboratories may be acceptable alternatives to hands-on laboratories, and that a larger similar study using the Second Life format is underway.

Several recent studies have investigated the relative effectiveness of simulated versus hands-on education laboratories and found simulated laboratory experiments to be equally effective or better than hands on laboratory experiments for the criteria measured. Three literature reviews have examined studies that investigated the effectiveness and acceptance of nontraditional laboratory formats compared to the traditional hands-on format. In the limited number of studies that directly compared simulated laboratories to hands-on laboratories published before 2005, the hands-on laboratory format appeared to be more effective (Ma and Nickerson, 2006). However, the trend in studies published after 2005 indicates that the simulated format may be equally effective or superior (Brinson, 2015). Improvements in virtual reality technology that allow more detailed and realistic virtual laboratories may account for this change. Brinson (2015) and Ma and Nickerson (2006) both concluded that a consensus has not been established on the goals of laboratory education among investigators, and this contributes to the debate about the relative effectiveness of different laboratory formats. Some professional organizations have considered this topic to be important and issued official positions that oppose the use of simulated laboratories as substitutes for hands-on laboratories (ACS, n.d.; NSTA, n.d.; Singer et al., 2006). The appropriate role for simulated laboratories in education is clearly a topic of interest and a topic of debate. A review of the goals of secondary laboratory education, and of the pros and cons of using simulated laboratories as substitutes for physical laboratories in secondary education is needed.

The learners I currently teach and the learners I will teach are in the Formal Operational Stage, so these learners can understand abstract concepts combine information and experiences to build new concepts and understandings (Myers, 2013). Laboratory education is supported by the constructivist theory (Shiland, 1999). During laboratory experiments, students learn by integrating new laboratory evidence and experiences into their current understandings to create new schemas (Shiland, 1999). This is consistent with the constructivist theory and the development characteristics of learners in the Formal Operational Stage.

Arguments for Laboratory Simulations

There are several reasonable arguments in favor of laboratory simulations. Simulated laboratories are less expensive than hands-on laboratories. Evidence from recent studies indicates that simulations may be as effective or more effective teaching tools, and the quality of simulations will likely improve as technology improves. Simulated lesson plans can be less time consuming since students do not spend time setting up laboratory equipment. Simulations are also inherently safer. Student mistakes in a simulation cannot cause physical harm to people, property, or the environment, but physical laboratories potentially can. Perhaps the best argument in favor of simulated laboratories is better accessibility.

Laboratory Costs

Simulations are time consuming and expensive to build, but after simulations are created, simulations can be used by an unlimited number of students, so the cost per use can be quite low (Brinson, 2015; De Jong et al., 2013). Hands-on laboratories are expensive to build and maintain (De Jong et al., 2013; Singer et al., 2006). Laboratory instruments and equipment are also expensive and may require highly trained technicians to maintain (De Jong et al., 2013; Singer et al., 2006). Some high school laboratories also generate hazardous waste. Hazardous waste storage and disposal must be in accordance with local, state, and federal regulations (Singer et al., 2006). Disposal and administrative costs to complying with local, state, and federal regulations are substantial (Singer et al., 2006). Laboratory accidents increase the cost of insurance and legal fees for school districts (Singer et al., 2006). The full cost of hands-on laboratories for large schools districts may be millions of dollars per year (Singer et al., 2006). Using simulated laboratories in place of traditional hands-on laboratories could be a wise use of limited education resources.

However, the cost effectiveness of a laboratory is more than just the cost per credit per student. The cost effectiveness of laboratories must include the quality of education and not just the costs of education. Because simulated laboratories are time consuming and expensive to create (Winkelmann et al., 2014), a limited number of simulated laboratory lessons will be created. Substitution of simulated laboratories for hands-on laboratories would limit the scope and variety of laboratory lessons available. High school laboratory instruments are expensive, but technical equipment and instruments in higher education and in industry are also expensive, so students should have the opportunity to learn to responsibly use technical equipment in secondary education laboratories (NSTA, n.d.). High school students should also learn to responsibly and legally manage waste streams (ACS, n.d.) and develop safe laboratory habits (NSTA, n.d.). Although simulated laboratories are less expensive, simulated laboratories do not provide all the same opportunities and value of traditional hands-on laboratories.

Effectiveness

The trend in recent studies indicates that simulated laboratories are as effective as or more effective than hands-on laboratories (Brinson, 2015; De Jong et al., 2013). This may be because students can concentrate on underlying principles rather than on the mechanics of laboratory set-up and data collection (De Jong et al., 2013). Data collection can be automatically collected, tabulated and graphed in real time within a simulation (De Jong et al., 2013). Students might also learn abstract concepts better from animations that draw attention to the most relevant aspects of an experiment (De Jong et al., 2013). Simulations can be repeated as often as needed which may help students learn difficult concepts (De Jong et al., 2013), but students often have only one opportunity to conduct a hands-on laboratory lesson. Given these possible advantages, it is not surprising that students score as well or better on formal examinations after completing a virtual laboratory lesson rather than a hands-on laboratory lesson.

On the other hand, most of the studies that indicate that students learn as well or better with laboratory simulations use formal examinations to measure content knowledge improvement only (Brinson, 2015; De Jong et al., 2013). NSTA (n.d.) recommends that authentic assessment tools for secondary education laboratories should measure inquiry skills, design skills, communication skills, analytical skills, and scientific thinking ability rather than assessing subject matter mastery alone. Automation of data collection and graphing in simulations does save time and effort that

can be used for learning content material, but automating these processes denies students the opportunity to practice and hone these analytical skills, and these skills are not assessed in most recent studies (Brinson, 2015; De Jong et al., 2013). Animations that highlight the most relevant parts of an experiment or illustrate normally invisible processes can be useful temporary scaffolding for learning content knowledge, but students will need to grasp concepts without such support in higher education and technology careers. Studies that indicate simulated laboratories are equivalent or better than hands-on laboratories do not assess all recommended laboratory learning goals with a variety of assessment tools.

Laboratory Time

Simulated laboratory lessons can be completed in less time than traditional laboratories (Brinson, 2015; De Jong et al., 2013). Students using a simulated laboratory do not spend time gathering equipment and materials (Brinson, 2015; De Jong et al., 2013). Students can start to learn as soon as they log-on to a laboratory simulation. Processes time for experiment operations like heating or cooling reactants can be shortened to complete more experiments in a class period (De Jong et al., 2013). In a simulation time spent manually logging data can be spent repeating experiments or in other leaning activities (De Jong et al., 2013). Laboratory simulations can reduce the time needed to complete experiments.

The time saving features above do have potential downsides. Gathering and setting-up equipment and materials teaches organizational skills as well as tactile skills using the equipment (De Jong et al., 2013). Compressing normal chemical and physical process times in simulations could create an unreal impression for students that would undermine confidence in experimental results. As was noted by Renken and Nunez (2013), repeated experimental trials may encourage less careful and lower quality experiments that do not enhance learning. Reducing the time required to complete experiments may not benefit students, and may not improve progress toward laboratory goals.

Safety

Simulated laboratory experiments pose no risk to student participants, to other people in the school, to larger community, or to the environment. A well-managed hands-on laboratory is not a major risk to the school or community (Singer et al., 2006), but incidents have injured instructors and prompted student evacuations in the past. (Teacher life-flighted, n.d.). Some interesting experiments cannot be conducted in secondary education because the reagents are too dangerous for high school students to use, but simulations offer the opportunity to conduct dangerous experiments even at extreme conditions (Singer et al., 2006). Simulated laboratories are safer alternatives to hands-on laboratories.

It is possible that the safety of simulated laboratories might not instill in students the proper respect and caution needed in higher education laboratories and industrial technology facilities. An explosion in a simulated laboratory might make the experiment more interesting and fun, but also might make the experiment seem too much like a game rather than a simulation of a real experiment that has dangerous potential. In hands-on laboratories, students learn to correctly use personal protection equipment and read a material safety data sheet, but students in a simulation would not have this learning opportunity. In hands-on laboratories, students learn the practical skills needed to safely use laboratory glassware, handle biological specimens, and handle

hazardous chemicals (Singer et al., 2006). Simulations may not prepare students to safely participate in laboratories in higher education or industry.

Hazardous Waste Management

Hazardous waste is generated in hands-on experiments and has to be disposed of legally and responsibly, and students should learn to responsibly deal with waste in education laboratories (Singer et al., 2006). Hazardous waste is not an issue for laboratory simulations, since no real materials are used or generated. This is both a strength and weakness of laboratory simulations. Simulations are more environmentally responsible since simulations generate no hazardous waste. On the other hand, simulations do not teach students responsible habits for chemical and biological waste disposal. Technological and scientific investigations benefit society, but also generate hazardous waste. Simulated laboratories do not emphasize this trade off the way that hands-on laboratories do.

Accessibility

Hands-on laboratories are less accessible than simulated laboratories. Hands-on laboratory lessons must be completed when laboratory time is available and when an instructor is available, but simulated laboratory lessons can be completed at times and locations that meet students' needs and convenience (Brinson, 2015). For distance learners, remote laboratories and simulated laboratories are the only laboratory options (Brinson, 2015). Simulated laboratories also allow absent students to make-up missed laboratory lessons and to complete laboratory assignments when a partner is unavailable. Simulated lessons are more convenient and accessible.

The greater accessibility of laboratory simulations does have some negative potential consequences. Laboratory simulations can be completed when an instructor is unavailable, but instructors provide guidance and support as needed during hands-on laboratory lessons. Laboratory simulations do allow assignments to be completed when lab partners are unavailable, but this does not provide the same social environment to support group discussions and learning. Completing laboratory lessons without partners will not facilitate development of collaboration skills which is a recognized laboratory goal.

Accommodate a Diverse Student Population

Simulated laboratories can accommodate the needs of a more diverse population of students. Simulated laboratories do not require the same motor control skills as hands-on laboratories, so a simulated laboratory may be a better option for students with motor control difficulties. Computer graphics can be modified and adapted for students with visually impairment (Milner, 2001), so simulated laboratories may be a better option for some students with visual impairment. Simulations do not have rigid time constraints (De Jong et al., 2013), so simulations can be completed by students who need more time. Simulated laboratories could make laboratory lessons available to a larger and more diverse group of students.

However, all students have a right to participate in laboratories to the fullest extent possible (Milner, 2001; NSTA, n.d.). Most students with special needs can safely and productively participate in hands-on laboratories with a thorough plan and proper accommodations (Milner, 2001). Proper accommodations may include, carefully planned laboratory work groups, architectural modifications for access and mobility, or inclusion of a directed laboratory assistant

(Milner, 2001). Students with special needs do not need to be limited to nor should they be limited to laboratory simulations.

Arguments Against Laboratory Simulations

Despite several valid arguments in favor of simulated laboratory use, there are three compelling reasons not to use laboratory simulations as substitutes for traditional hands-on laboratories. Professional education organizations support the use of laboratory simulations as supplements to hands-on laboratories but not as replacements for traditional hands-on laboratories. The evidence for simulated laboratory equivalence to traditional hands-on laboratories is not convincing. Laboratory simulations are not an ideal format for achieving several of the goals identified by the National Resource Council. Traditional hands-on laboratories continue to be supported by education and science professionals because hands-on laboratories have a proven capacity to meet all laboratory education goals.

Professional Organizations

Professional science and education organizations are opposed to the use of laboratory simulations as substitutes for hands-on laboratories. The American Chemical Society recognizes the value of laboratory simulations to enhance learning, but does not recognize laboratory simulations as equivalent or acceptable substitutes for genuine laboratory experience (ACS, n.d.). The National Research Council also notes the merits of simulated laboratories, but states that simulations should be used to supplement rather than replace hands-on laboratories. (Singer et al., 2006) The College Board supports the use of computers in laboratory education but requires hands-on inquiry based laboratory lessons be a part of the AP Chemistry curriculum (College Board, n.d.). The National Science Teachers Association supports the use of laboratory simulations but does not support the use of laboratory simulations in place of traditional hands-on laboratory lessons. Professional science and education organizations have recognized the importance of this issue and are supportive of the use of computer simulations in science education but insist that hands-on laboratory experience is a necessary part of science education.

Insufficient Evidence for Equivalence

In recent studies the effectiveness of laboratory simulations was measured primarily by assessing improvements in content knowledge. No recent study assessed progress toward all seven goals identified by the National Research Council. Hawkins and Phelps (2013) assessed mastery of subject matter and practical skills. Yang and Heh (2007) assessed mastery of subject matter and science process skills. The four other recent investigations reviewed here only assessed the mastery of subject matter goal. Recent studies do not provide evidence for the equivalence of simulated laboratories in meeting most laboratory education goals identified by the National Research Council.

Recent studies which compared simulated laboratories to hands-on laboratories were short duration studies where students completed a small number of laboratory lessons. Yang and Heh (2007) investigated hands-on and virtual laboratory experiments and included four experiment lessons. Pyatt and Sims (2012) investigated hands-on and virtual laboratory experiments and included two experiment lessons. The four other recent investigations reviewed here included only one experiment lesson. If all hands-on laboratory lessons were replaced with simulated laboratory lessons for a semester or for a year, the education outcome is uncertain. It is plausible that students

achieved success in improving content knowledge using simulated laboratories because the students had already developed analytical skills and an understanding of science in traditional hands-on laboratories. Studies that include a large number of simulated laboratory lessons are needed to prove that simulated laboratories are equivalent to hands-on laboratories.

Simulations Are Not the Best Format for Most Laboratory Goals

The traditional hands-on format is a better format to build teamwork abilities. It is common to work in pairs or groups in traditional laboratories. Students must work as a team to be successful. Team building activities include laboratory apparatus set-up, data collection, data analysis, problem solving, and final report production. Group discussions are required to reach consensus conclusions for traditional laboratory lessons. On the other hand, interactions with a computer lesson are often solo activities without synchronous direct communication with peers and without direct cooperation with peers. Traditional hands-on laboratories build team work skills (Singer et al., 2006). Laboratory simulations are not the best choice for building teamwork skills.

One of the National Research Council laboratory goals is developing an appreciation of the uncertainties, ambiguities, and complexities of laboratory work (Singer et al., 2006). Unexpected problems and surprising results are a part of real laboratory work (De Jong et al., 2013). Every event and outcome in a simulation is by definition an anticipated event since every event and outcome has been built into the simulation by a simulation designer. The designer may introduce some limited programmed randomness, but cannot build in the open-ended nature of real laboratory events (De Jong et al., 2013). Simulations also produce clean unambiguous data (De Jong et al., 2013). A full appreciation of the complicated and sometimes ambiguous nature of empirical work can only be developed by working in a real empirical setting.

A goal of laboratory lessons is to build an interest in science (Singer et al., 2006). A simulation does not provide a full laboratory experience, and the current number of laboratory simulations available is limited. Students should have the opportunity to experience a full laboratory experience through a large variety of laboratory lessons which may be more engaging and interesting than a limited number of computer simulations. Students need a real laboratory experience to decide if they have the desire and interest to pursue experimental or analytical science careers or technology careers, but students who experience science experiments only through simulations gain a limited artificial laboratory experience.

Traditional hands-on laboratories are a better format for developing scientific reasoning because traditional laboratories can be more open-ended. In hands-on laboratories, students should be encouraged to generate investigation ideas, determine relevant variables, analyze data, and draw conclusions (College Board, n.d.). Students in hands-on laboratories can generate and explore investigation ideas, but laboratory simulations are limited to the investigation ideas that have been programmed into an available simulation. The variables of an experiment are built-in to a laboratory simulation, so students do not have the opportunity to determine the relevant variables of an investigation. The complexity and ambiguities of traditional laboratories also encourage the development of scientific reasoning. The traditional hands-on format is a better choice for developing scientific reasoning.

The traditional hands-on laboratory format is the only choice for developing practical skills. Students do not organize or set up simulated laboratory experiments, so do not build organization skills. Students do not physically operate laboratory equipment in simulated laboratories, so do not learn to use laboratory equipment. Students do not have the opportunity to practice precise motor skills and measurements in simulated laboratories. In simulations data gathering and organization is often automatic (De Jong et al., 2013). In simulations students do not need to organize data and record observations in a laboratory log (De Jong et al., 2013) which is often required in higher education and industry. Developing practical laboratory skills is a recognized goal of laboratory education (Singer et al., 2006), and simulated laboratories do not help students achieve this goal.

Implications for Practice

Educators need to build a body of evidence for simulated laboratory use. Educators should gradually introduce simulated laboratories into secondary education. Simulations should be used as preparations for traditional laboratories and effectiveness should be assessed. Simulations should be used to explore topics that cannot be explored with traditional laboratories and effectiveness should be assessed. Instructors should use simulated laboratories as substitutes for traditional laboratories with caution and assess progress with a variety of assessment tools against all standard laboratory goals and with all student groups. Gradually introduction of simulated laboratories into secondary education will allow education professionals to assess the most productive way to use this valuable technology and determine the appropriate role for virtual laboratories in secondary education.

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