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Final Paper - Literature Review: Educational Computer Simulations

Introduction

Utilizing technology in the classroom is "all the rage" these days – this is common knowledge in not only educational circles but also in the public consciousness. But contrary to the popular opinion of this being a modern phenomenon, both computer and physical simulations have been used for educational purposes for longer than my lifetime. Lunetta and Hoffstein (1981) cite Glazer as studying the use of simulations in military training as early as 1960. Both enthusiasm and criticism have followed, stemming from researchers, educators, learners, and the general public. It might be expected that in the intervening years many questions would have been settled about the educational use of technology, however as the power of computers has advanced (from mainframes the size of a room to iPhones that fit in a pocket) so too have the educational uses of computers. While studies of the use of technology have also advanced, there remains much to be investigated still.

Definition

Gagné's 1962 definition of a simulation (as quoted in Lunetta and Hoffstein, 1981) is:

1. A simulation represents a real situation in which operations are carried out.
2. A simulation provides the user with certain controls over the problem or situation.
3. A simulation omits certain distracting variables which are irrelevant or unimportant for the particular instructional goals.
   Simulation = (Reality) – (Task irrelevant elements)

This definition encompasses models both digital and analog, allowing us to compare computer-based simulations to more traditional classroom demonstrations and laboratory experiments.

Chen, et al. (2007), further explores this idea in the context of virtual realities (VR). They define a VR as a computer system providing "visualization, interactivity, and immersion", and specify that it can be broken down into three types, "Type I: interpersonal communication, Type II: information browsing, Type III: hands-on experience" (Chen, et al., 2007).

In this work I will be focusing on educational physics and astronomy simulations designed to be run on a desktop or laptop computer (as opposed to on a tablet, smartphone, or other hardware). The vast majority of these simulations fall into the Chen, et al. (2007) definition of Type III VR: hands-on experiences. Although in many of the studies discussed herein the educational computer simulation (ECS) is used in conjunction with interpersonal communication, these interactions usually take place in the real world and are secondary to the educational goal of the ECS, rather than having the interaction be mediated by and/or necessary to the ECS.

Other Terms in the Literature

Koops and Hoevenaar (2012) do not explicitly define their term "serious game", but they do distinguish it from computer simulations and applets. "Serious game" refers to a computer program designed to have a user experience more akin to that of games for entertainment purposes, as opposed to ECSs which are designed for the user to have an experience more like that of a physical lab; a serious game is designed for the student to have a stealth learning experience. The design of serious games appears to have different considerations than that of ECSs, so their is outside the scope of this review. However, the practical implementation of serious games in the classroom has very similar considerations to implementing ECSs, and so is within the scope of this review.

Motivation

While physics courses can often use physical labs for students to explore or confirm concepts, in astronomy it is not always possible to study all topics in the laboratory setting. In both physics and astronomy, there are some topics where labs involve many extraneous and unnecessary complicating factors (e.g., air friction, inherent measurement errors, time) that are difficult or expensive to mitigate. Even where physical labs are possible, computer simulations allow teachers greater options of labs to offer, for example if the school does not have access to equipment due to constraints of space, cost, or training. In astronomy, there is the further difficulty of many labs requiring clear dark skies.

In addition to being used to replace physical labs, ECSs can also be used during non-lab classroom time, as a partial replacement for or supplement to more traditional objectivist lectures, or outside classroom time. Research has shown that nearly any teaching style is more effective than lecture, and ECSs allow teachers who use the objectivist teaching style to quickly and easily demonstrate the concepts they wish to lecture about. Should a teacher instead follow a somewhat more constructivist philosophy, she can instead use ECSs in the style known as Interactive Lecture Demonstrations (ILDs), where the instructor asks the students to predict the outcome of an experiment, in this case the outcome of a simulation given specific input parameters, and after the students make a prediction the experiment is then performed and students reflect on whether and why they were correct or incorrect.

The many branches of science increasingly use computers in the data-taking process as well as data analysis. Students of science need to become comfortable with computers early in their careers. Even students who are not going to go into science need to understand the importance of computers – there are many misconceptions in the public about computer analysis of data, for example thinking that necessary steps of data reduction are equivalent to faking data.

Questions to be Addressed

I hope to address the following topics in this literature review. How effective are ECSs compared to lecture, problem solving, videos, traditional hands-on labs, and classroom demos? What are the most effective ways to implement ECSs? What barriers exist to students' optimal learning with ECSs?

Summary of Studies

With the many decades of study of ECSs, there are four main facts that we know: simulations are better than no instruction at all; simulations are better than many other alternative pedagogies; so far the only significant factor influencing student learning in different implementations of ECSs is cognitive load; and all types of ECS result in greater transfer than traditional lecture.

Simulations are better than no instruction at all

Although it seems intuitive that any particular teaching method should be better for student learning than not teaching students at all, this is not actually the case. Education researchers have known for years that the traditional objectivist lecture does not always result in an increase in student knowledge, as shown by negligible gains in pre-post tests such as the Force Concept Inventory (Hake, 1998). Therefore I feel that even the least rigorous of studies that only compare pre- and post-test scores can still be compared to the benchmark of zero gains in the case of no instruction or lecture. It is fortunate that such a comparison can still be made, because the field of ECS is riddled with studies lacking a true control.

Two prime examples are the studies of Cox, Belloni, and Christian (2005) and Chen, et al. (2007). Both groups developed a lesson around a specific ECS, gave it to a small sample of students, and found that the students demonstrated significant learning. Cox, Belloni, and Christian (2005) combined ranking tasks with a Physlet (see Christian, 2005-2013, in Appendix) ECS, and found that the five students in their sample were able to recreate Gauss's Laws as evidenced in a think-aloud protocol. While Chen, et al. (2007) is a great resource for its extensive literature review section, their study also lacked a control. Twenty-one sixth grade students received a lecture on Earth motions, then were given questions to focus their exploration of a related simulation. These students showed significant gains between pre- and post-test scores on 13 common misconceptions common to children about the motion of the Earth.

Simulations are better than other pedagogies

More rigorous studies follow a quasi-experimental setup, where two groups of students receive different forms of instruction and their outcomes are compared. The "experimental" part of the name comes from the fact that two different groups are compared, either with one being a control (e.g., lecture, traditional labs, or whatever style the professor was using before the intervention), or with both being different versions of ECSs. The "quasi" comes from the selection of the two student samples not being entirely random but instead being based upon the students' own choice of one course section over another. Through studies of this type, we have found that students learn more and retain more via ECSs than lecture, other non-lecture instruction, textbook problems, or worked examples.

McKagan, et al. (2008) is a reason example of this next step of studies, in that they actually did attempt to introduce a control. In their study, they compared post-test scores across a number of different pedagogies, including lecture, other non-lecture instruction, and ECS, on the topic of the photoelectric effect in an undergraduate sophomore-level modern physics course. Students learning via the ECS had significantly higher post-test scores than students in the other groups, however the findings of this study would have been significantly strengthened had the researchers conducted a pre-test to ascertain students' prior knowledge.

The only difference in ways of implementing ECS is cognitive load

A number of different studies have attempted to probe different ways of implementing ECSs. Many of these have found zero statistical significance between the two methods studied. In the cases where differences have been found, the researchers have speculated that the root cause is one of cognitive load. There are hints that students appear to reach the limit of their working memory sooner when using ECSs than when using physical lab equipment, although this has not yet been rigorously tested.

Meier, et al. (2008) provides an example of two implementations of ECS with no significant difference in student outcomes. In a forensic science class with 39 undergraduate students, they developed two versions of an ECS. Both versions of included worked examples, but one version included further elaboration such as explaining why a scientist took the specific actions, or why certain characteristics led to a specific conclusion. All students performed both styles of ECS, with half of the students performed one version first, and the other the other version first. They found that students in the two groups did not have statistically significant differences in their learning.

Koops and Hoevenaar (2012) also found a null result in their study of two versions of a "serious game" about Newtonian forces, in which the difference was the rate at which the difficulty of the game was increased. They expected that the version with more rapid difficulty increases would push students out of the gaming flow and into a state of metacognition where they would reflect upon the game rules they were learning (called the "switch" group), and that this would result in increased learning. This study was performed upon Dutch high school students, 17 in the control group (lecture, discussion, problem solving), 14 in the game group, and 10 in the switch group. Both sets of students using the serious game learned more than the control group, however there was no significant difference between the game and the switch groups. Observation of teacher interactions with the students indicated that teacher support was required to scaffold the students in the use of the interface.

Lee, Nicholl, and Brooks (2004) studied two separate implementations of an ECS on the ballistic pendulum. One implementation was simpler, showing only a few select worked example problems, while the other was more free-form, allowing students to vary input parameters at will. In their study of 77 students in algebra-based college physics, they found that students who used the simpler version not only had assignment scores that were significantly higher than students who had the more free-form version, but they also found that these students were more likely to utilize the opportunity to repeat the assignment, they had higher scores per attempt, and that they had a higher overall course score. They attributed these differences to an issue of frustration due to cognitive load.

Transfer

Students taught via ECS are better able to transfer their knowledge to other fields. Koops and Hoevenaar (2012) found that both of their ECS groups had more transfer of the ideas from their serious physics game to the FCI (Hake, 1998) than did the control group. In addition to performing a post-test in the same subject of forensic science, Meier, et al. (2008) also performed a test of transfer by having their students complete a post-test on archaeology. They found that both groups had similar levels of transfer to each other, and that their scores on the transfer post-test were similar to their scores on the same domain (forensic science) post-test.

Other things we know: Student attitudes

The question of student attitudes towards ECSs has not been as extensively studied as other aspects of the field. This facet is rich with opportunity for future research, building upon the few things that are known.

Although the nominal purpose of Zacaharia's 2003 study was to determine if pre- and in-service teachers are more likely to use ECSs after experiencing them as a student, he did not explicitly test this but instead tested their attitude towards using them in the future. He studied a class of 13 physics education graduate students, and found that after a semester of implementing ECSs in the classroom, these students were more able to identify the strengths of such instruction and to express that they were likely to use them than they were at the start of the semester.

Windschitl and Andre (1998) investigated using ECSs in a constructivist and objectivist setting, also surveying students about their attitudes as regards learning. Unsurprisingly, they found that those students who held more constructivist beliefs did better using an ECS in a constructivist setting, while those who held more objectivist beliefs did better in an objectivist setting, and this appeared to be primarily due to differences in the constructivist students' learning in the two environments. This study was performed on 250 students in an undergraduate non-majors course on human anatomy and physiology, and the specific ECS was on the human cardiovascular system.

Summary

Taking this all together, we know that ECSs are better than no instruction or lecture (of course), they are better than other forms of instruction, they can lead to greater transfer than lecture, and that cognitive load remains a challenge in implementing ECSs.

Future Work

Although we have learned much in recent decades about ECSs, there is still much yet to be done. The most surprising of these in my opinion was how many of the studies were lacking in rigor. Many of the papers in the field are of the "best practices" style (that is, they describe what the author feels is the best way to teach, without providing any evidence whatsoever).

Even once researchers begin to move past this to performing studies, there are still often flaws, ranging from complete lack of any control, to lack of a pre-test to eliminate any remaining bias in the quasi-experimental nature of many of these studies. For example, the McKagan, et al. (2008) study found that students learning the photoelectric effect via an ECS had better post-test scores than students learning via other methods, however all the sections using ECS were offered in Spring semesters while all the other sections were during Fall semesters. Using a pre-test and looking at gains would allow the researchers to eliminate other factors, for example if students in one of the semester were more likely to be retaking the course, or were out of synch with the majority of their cohort for some other reason such as math prerequisites.

As it currently appears inconclusive whether different styles of using ECS are different, this sub-field is ripe for further research, both with exploring more pedagogies and using larger sample sizes for existing studies. The only thing in this sub-field which has so far aroused the interest of researchers is the role of cognitive load, however so far this tie has only been implied and not explicitly tested.

Based upon what I have been able to find, there are three specific ideas that do not appear to have been studied at all. There appears to be no general survey of ECS topics, there is a dearth of studies on interface design, and there are no studies on the use of ECSs as interactive lecture demonstrations (ILDs).

Limited survey of topics

I was to find any general survey of topics for which ECSs have been created. While Chen, et al. (2007) briefly surveyed the four astronomy VRs and their target audiences, their paper did not address the effectiveness of these tools, and its scope was limited. It may be that some topics are better suited to being taught via an ECS, or that certain pedagogies will work best in certain topics, or even that cognitive load may be more or less of a factor in different topics.

Human-Computer Interaction

There appear to be no studies on interface design (also referred to as HCI, human-computer interaction or interface) with ECSs. This is an important consideration in “serious games”, so it is surprising to me that the related field of ECSs appears to have no significant research specifically addressing this topic. While there has been work done on many topics related to HCI – for example, the works by Windschitl and Andre (1998) and by Lee, Nicholl, and Brooks (2004) both have implications for design of ECSs – none of these studies specifically refer to the idea of HCI, nor were these studies undertaken with the specific purpose of redesigning the ECS interface for optimal student learning.

Interactive Lecture Demonstrations

All but one of the studies I was able to find implemented the ECSs in a setting similar to that of a traditional physical lab, where all students are located in the same room at the same time, there is one computer per individual student or per small group, and the teacher is also physically present to work with students. Only a single study (Lee, Nicholl, and Brooks, 2004) had the ECSs used in a different setting – these students performed the ECSs on their own time on individual computers.

The term "interactive lecture demonstration" (ILD) refers to a setting in which an instructor poses a question to her students by describing an experiment about to be performed. The students are encouraged to make a prediction about the experiment's outcome and discuss with their peers, including an explanation for their prediction. The instructor then performs the experiment, and the students are encouraged to reflect upon the outcome, how it compares to their prediction, and revise their ideas as necessary.

ILDs are a great step for instructors to move from an objectivist (lecture) style of teaching towards engaging students more actively. An ECS can be used in an ILD format if the instructor has a single computer with a display visible to all students, the instructor poses a question to the entire class about the ECS, waits until students have made a prediction, and then uses the ECS to demonstrate what would actually happen. I did not find any papers referring to this method of using ILDs. As many science education researchers attempt to move science instructors from objectivist teaching towards more constructivist teaching, the apparent lack of papers on this was surprising to me.

Conclusion

In this paper I have addressed some of the resolved questions in the field of ECSs. We know that ECSs are more effective than a variety of other teaching styles, including lecture, problem-solving, and other more active instruction. We know that one of the biggest challenges to implementing ECSs is mitigating students' cognitive load, and that teacher support during the use of the ECS goes a long way towards doing so.

But despite these answers and the many decades of using computer simulations in an educational context, the main things that researchers have learned have simply been more questions. Why is it that different styles of implementing ECSs make no difference? How (in detail) does cognitive load affect student learning while using ECSs? The few things that we do know may have even been self-evident before the research was performed, so there is much yet for us to learn.

The field of educational computer simulations is ripe for more research to be performed, and I look forward to boldly jumping into it!

Appendix: Annotated Bibliography of Example Libraries

While the papers discussed herein tend to focus on the use of one individual ECS at a time, there exist a number of libraries of many ECSs across the fields of physics and astronomy. Below is an annotated bibliography of a few of these libraries.

Christian, Wolfgang (Davidson College). 2005-2013. "Physlets Home Page." http://webphysics.davidson.edu/Applets/Applets.html . Within the field of ECSs, perhaps the best-known library of applets is that of Physlets, authored by Wolfgang Christian at Davidson College. These simulations are available for public non-profit educational use. Physlets are commonly described as "web-based applets about physics" (e.g., Lee, et al., 2004; Cox, et al., 2005).

Lee, Kevin (University of Nebraska - Lincoln). 2013. "Astronomy Simulations and Animations (UNL)." http://astro.unl.edu/animationsLinks.html . The University of Nebraska-Lincoln astronomy department hosts a large library of astronomy ECSs under the direction of Kevin Lee. These are publically available, and appear to be the largest library of astronomy-specific ECSs.

Mason, Bruce, Susana (AAS) Destua, Jack (AIP) Hehn, Warren (AAPT) Hein, and Theodore (APS) Hodapp. 2013. "Compadre.org Homepage". ComPADRE Digital Library. http://www.compadre.org/ . The ComPADRE library, managed by Bruce Mason, et al., is the most comprehensive astronomy and physics teaching resource available, and is a joint project of the AAPT, AAS, AIP/SPS, and APS. The scope of this site is exhaustive, including simulations, multimedia, lesson plans, and author/educator/student discussion communities.

PhET Interactive Simulations, (University of Colorado). 2013. "Physics - PhET Simulations." http://phet.colorado.edu/en/simulations/category/physics/index . The PhET Interactive Simulations Project out of the University of Colorado originally focused on physics educational technology (hence the name), but has since branched out to other STEM fields. Their database is provided under a Creative Commons license.

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