Systematic Review and Meta-Analysis of STEM Simulations

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Abstract: This paper describes the initial findings of a systematic meta-analysis of the literature of computer simulations related to science, technology, engineering, and mathematics (STEM) learning. Features of the simulations, quality of the research design, and the assessments/instruments used to measure learning are the primary moderating variables of interest. A meta-analysis of 55 research studies of K-12 science education, published between 1991 and 2012, found that on average simulations had a positive effect on science achievement.

Study Overview

This paper presents an overview of the process and initial findings of a systematic review and meta-analysis of the literature of computer simulations related to K-12 science, technology, engineering, and mathematics (STEM) learning topics. Both quantitative and qualitative research studies that examined the effects of simulation in STEM in the K-12 grade range were included in the study. Of these studies, those that reported effect size measures (or the data to calculate effect sizes) were included in the meta-analysis. Important moderating factors related to simulation design, assessment, implementation, and study quality were coded, categorized and analyzed for all of the included articles.

The simulation meta-analysis and review take a systematic look at the research and evidence surrounding learning STEM topics through computer simulations. We are primarily focused on answering three research questions:

(1) What are the advantages of using simulations compared to not using simulations in STEM learning contexts?

(2) What are the advantages of using simulations alongside real-world laboratory or classroom activities compared to using simulations alone?

(3) What types of features or modifications to simulations are most beneficial for learning?

We documented a variety of dependent variables related to these questions, including content-related learning goals, 21st century skill learning goals, and engagement/motivation-related learning goals. Additionally, moderating variables and assessments used to determine learning outcomes were coded and analyzed.

Initial Literature Search

This study focused on computer-based simulations that are neither simple visualizations nor games. Some of these simulations simulated a virtual lab environment (such as a virtual frog dissection), while others represented a more abstract scientific phenomenon (such as structure at the molecular level). All of the simulations had some level of user interactivity, usually in the form of specific inputs that could be changed.

Three databases that were selected: the Education Resources Information Center (ERIC) (http://www.eric.ed.gov/), PsycINFO (http://www.apa.org/psycinfo/), and Scopus (http://www.scopus.com/). These databases were searched for only peer-reviewed journal articles published between 1991 and 2012 (inclusive). The initial search terms included the STEM domains (science, technology, engineering, and mathematics and their subtopics – such as biology and chemistry) and "simulation" or "computer simulation" as primary search terms.

From the database search 2392 abstracts were collected and reviewed by the research team. The abstracts were screened for suitability and exclusion criteria. Most abstracts were excluded for focusing outside of the K-12 grade range, for not including a research study (quantitative, qualitative, or mixed methods), for not being related to STEM content, or for the simulation not being used in a instructional setting. This screening resulted in full-text retrieval of about 200 primary research studies potentially suitable for the analysis.

Article Review and Coding

Through a thorough review of full-text documents, 133 studies were retained for further analysis. Of these, 49 were determined to be research articles including either an experimental or quasi-experimental design. Of those, 9 were determined to contain incomplete or repeated data for this current analysis. The remaining 40 studies yielded 104 effect sizes, 67 of which were in the achievement outcome category, 11 were in the attitudes category, and the remaining 26 that fell into other categories (such as inquiry skills).

The research team coded the articles, with each article being coded by two researchers. The article codes fall into six broad categories: demographic information (location of study, ages of participants, language of instruction); study information (research question, STEM topic); methodological information (research design, group equivalency, attrition); assessment information (source of assessment, type of measures); simulation information (type, collaboration, flexibility, platform); and implementation information (setting, curriculum, time/duration/frequency).

Meta-Analysis Results

Many descriptive characteristics of the comparisons can be reported at this time. Most of the studies were in the domain of science and a few were in mathematics. Follow-up and cross-checking is currently underway to increase the number of mathematics studies. Most of the studies were conducted in either North America or Europe. About 60% of the participants were in high school, while most of the remaining participants were in middle school. Nearly all of the studies were conducted in classrooms. Nearly all of the simulations were either embedded in the classroom curriculum or used as related stand-alone instruction. Most of the simulations could be used collaboratively among students (but not all were implemented this way) and had some structured use (i.e., they were not totally open sandbox environments or highly structured). Assessments used in measuring student outcomes were by and large not technology-based and the vast majority of assessment instruments were researcher-designed.

Seven methodological characteristics were identified, coded and tested to determine if the collection of studies contained systematic bias due to methods employed by primary researchers that might alter the interpretation of results. We concluded that there is no severe bias due to the research practices contained in the collection.

These initial findings indicate that simulations have promise for improving students' learning outcomes in STEM topics. While further analysis needs to be done both with this corpus of studies and the qualitative and pre-experimental studies identified in the literature search, there are many high level findings that can be discussed at this time.

The meta-analysis found, based on 33 science education research studies, that when computer-based interactive simulations were compared to similar instruction without simulations there was a moderate to strong effect in favor of simulations ($g+ = 0.67$, $z = 10.07$, $p < .000$).

The meta-analysis of 22 additional studies, where simulations were modified to include further enhancements, showed that the enhanced simulations had a moderate effect on student learning when compared to the simulations alone ($g+ = 0.43$, $z = 4.39$, $p < .000$). These enhancements included modifications such as additional scaffolding, feedback, and changing group structures. Scaffolding can be thought of as systematic supports for learners. As this project continues we are examining the details of these learner supports, among other things.

Next Steps and Implications

There is ongoing work on this project to broaden the search criteria in order to ensure that math simulations are included (we only had a handful of math-related studies using the initial search terms). We are also going back and hand checking other review articles to look for important and "landmark" articles that might have been missed. Additionally, we will be coding and reviewing the qualitative studies that met our initial search criteria, in order to help understand why and under what conditions and contexts these learning gains are occurring.

These preliminary results have many implications for science education. They show that simulations can have a significant impact on student learning and are promising tools for improving student achievement in science. Simulations are a key way that students interact with models (an important focus in the new science Framework), especially models based on phenomena that are difficult to observe in the typical classroom setting (due to reasons such as scale, time, safety, or budget limitations). The new K-12 Science Framework (National Research Council, 2012) and the resulting Next Generation Science Standards (NGSS) will be framing the discussion about science education research (and STEM education research more broadly) in the near future.

There are sufficient numbers of studies in this area to allow for detailed further analyses relating to the mechanisms and features that allow for improved learning through simulations. Continued efforts in this area will reveal more information about the assessments used to measure learning. Findings relating to attitudes, inquiry, and reasoning skills are less clear at the moment, due to the low number of studies focusing on these outcomes.

References

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