Review of Computer-based Simulations for STEM Learning in K-12 Education

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May 2013

Purpose

The rise in computing has been accompanied by a decrease in the costs of computers and an increase in the use of simulations for learning and training. In the STEM field in particular, real equipment can be difficult to obtain, dangerous to operate, and cost prohibitive, so simulations let students experience and investigate scientific phenomena they normally would not be able to experience firsthand. The potential benefits of simulations, such as allowing for new phenomenon to be investigated at different physical scales and time periods, have led some individuals to believe that using simulations in the classroom can help improve learning.

Several recent literature reviews (e.g., Smetana & Bell, 2012; Scalise, et al. 2011) have focused on whether and in what ways simulations aid the improvement of student learning. Some of these reviews are focused on a very narrow range of simulation studies while others are focused only on overall trends of the findings of these studies, but none conducted a comprehensive quantitative meta-analysis. To date, the simulation literature has not been systematically reviewed and quantitatively summarized to determine if simulations do in fact have an effect on K-12 student learning.

This review addresses this gap in the current research literature on computer-based simulations for STEM learning. It was conducted by a team of researchers at SRI International under a contract with the Bill & Melinda Gates Foundation. A simulation, for the purposes of this review, was defined as a computer-based, interactive environment with an underlying model. The review focused on effects of and the role of computer-based simulations for learning in K-12 education in the areas of STEM education.

This review focused on computer-based simulations that are neither simple visualizations nor games, recognizing that a continuum exists among these types of digital tools. For the purposes of this review, simulations needed to be constructed with an underlying model that was based on some real-world behavior or natural/scientific phenomena (such as models of the ecosystem, or simulated animal dissections). In addition, all studies included in the review are characterized by simulations that include some amount of user interactivity, centered on inputs and outputs of the model.

This review examined studies that compared simulation-based instruction to non-simulation-based instruction as well as studies that compared two versions of simulation-based instruction to each other.

Developed by SRI International with funding from the Bill & Melinda Gates Foundation.
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This report is based on research funded by the Bill & Melinda Gates Foundation. The findings and conclusions contained within are those of the authors and do not necessarily reflect positions or policies of the Bill & Melinda Gates Foundation.

Meta-Analysis Approach

A meta-analysis is the systematic synthesis of quantitative results from a collection of studies (Borenstein, et al., 2009) focused on a given topic. Part of the systematic approach in a meta-analysis is to document the decisions that are being made as to the collection of the articles and the steps of the analysis. In a meta-analysis, articles are included based on pre-defined criteria and not due to favorable results found in the article or familiarity with certain authors. This can help to remove some of the bias and subjectivity that would result from a less systematic review.

Meta-analysis quantifies results by using effect sizes. Effect sizes are a measure of the difference between two groups. In the case of an intervention, an effect size can be thought of as a measure of the (standardized) difference between the control group and the treatment group, thereby providing a measure of the effect of the intervention. Effect sizes are not the same as statistically significant differences that are typically reported and determined through the use of inferential statistics, such as t-tests or ANOVAs. A research study, for example, could have a statistically significant finding, but the effect of that difference could be minimal. Thus the effect size allows researchers to determine the magnitude of the impact of an intervention, not just whether or not the intervention made a difference. For example, an effect size of 1.00 would be interpreted as a difference of one standard deviation between the two groups being compared. Another way of interpreting a one standard deviation effect size would be moving a student at the 50th percentile before the intervention to the 84th percentile after the intervention.

Search Criteria

The initial search criteria for this meta-analysis study were peer-reviewed journal articles published between 1991 and 2012, using three databases (ERIC, PsychINFO, and Scopus) and the search terms "simulation" paired with various STEM terms (such as "science education" and "mathematics education"). A total of 2,392 articles were identified as part of this initial search. A team of researchers screened the abstracts of these articles to ensure a match with study inclusion criteria. 133 articles met our initial criteria. We examined these 133 studies and found a total of 40 unique studies that were either experimental (i.e., random assignment with treatment and control groups) or quasi-experimental (i.e., not randomized but with treatment and control groups).

For each of the 40 included studies, reviewers identified the study's participants and settings, research questions and results, research methodology, assessment instrument information, implementation information, and a description of the simulation used in the study.

Preliminary Meta-analysis Results

From these included 40 studies we extracted 104 effect sizes; 67 of these effects were in the achievement outcome category, 11 were attitudinal outcomes, and the remaining 26 fell into other outcome categories (such as inquiry skills).

These effect sizes were further categorized according to STEM areas and research questions. In the area of science achievement outcomes, we have a sufficient number of effect sizes to report findings at this time. For the other STEM area outcomes, there were too few effect sizes to report any findings in this preliminary report.

When computer-based interactive simulations are 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 improvement index (i.e., percentage of increase between the control mean and the treatment mean) was 24.86%. This means that the achievement of students at the median in the control group (no simulation) could have increased 25% if they had received the simulation treatment.

When computer-based interactive simulations were modified to include further enhancements (such as additional learner scaffolding and certain kinds of feedback), the enhanced simulations had a moderate effect on student learning above the non-enhanced simulations ($g+ = 0.43$, $z = 4.39$, $p < .000$). The improvement index was 16.64%.

Some of the outcomes of interest (such as mathematics achievement or attitudinal measures) included only a few studies. At this preliminary stage, for example, we cannot make any statements about the impact of computer-based simulations in the areas of mathematics education. Additional search criteria were added and more articles reviewed for the final report. Likewise, the impact of computer-based simulations on student attitudes, inquiry, and reasoning skills is unclear due to low numbers of studies focusing on these outcomes. These low numbers may be improved with the additional mathematics articles. Despite the large number of college-level engineering education studies, there are very few studies of computer-based simulations for learning in the area of engineering education for K-12 aged students.

Preliminary Descriptive Results

In the area of science learning, on average, computer-based simulations had a positive effect on student science achievement. Some enhancements to computer-based simulations (such as additional learner scaffolding, feedback, and specific group structures for collaborative work) further increased the benefits to student learning, in some settings and under some conditions. There are only a few effect sizes in each of the enhancement categories, however studies involving cooperative learning arrangements, scaffolding, and feedback had some of the largest effect sizes.

Characteristics of assessments used in these simulations studies were examined as part of this analysis. Although the simulations were necessarily technology-based, very few of the measures used to assess student learning in the simulations were technology-based. 31% of the studies involving a comparison between two simulations clearly used a technology-based delivery mode of assessment. Additionally, the majority of effect sizes (81%) were from studies where the measures of learning were researcher developed. Continued work is underway to further categorize the characteristics and technical qualities of the measures used in these studies.

Implications

These preliminary findings will help GlassLab (glasslab-games.org) and other educational simulation designers make appropriate, research-based decisions in developing new educational materials for students. Teachers, researchers, and policy makers will also gain insight about how simulations can impact STEM learning. Knowing what features of simulations and implementation factors have contributed to positive effects in past simulation studies can help educators and researchers plan what is likely to work in current projects (including the specific contexts and settings where those successes occurred). The continuation of this meta-analysis will deepen and broaden what we know about past computer-based simulation studies and guide the design of future studies.

Engineering education will play a larger role in K-12 settings than it has previously due to the changes recommended by the new Framework for K-12 Science Education (NRC, 2012) and the Next Generation Science Standards (NGSS) (Achieve, 2013). The Framework identifies specific scientific and engineering practices as well as crosscutting concepts that “unify the study of science and engineering through their common application across fields” (NRC, p. 2). The field needs more research done in this area in order to understand how the benefits of computer-based simulations can be brought into K-12 engineering education.

Conclusion

These preliminary findings have many broad implications for the field of science education. They show that simulations can have a significant positive 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).

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