Improving Higher-Order Learning and Critical Thinking Skills Using Virtual and Simulated Science Laboratory Experiments

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Abstract
Laboratory experiences are a vital component within science education. This paper is a report on the findings of a study conducted on undergraduate level laboratory science courses. A causal-comparative quantitative study was conducted with 150 learners enrolled at a 2-year community college, to determine the effects of simulation laboratory experiments on Higher-Order Learning, Critical Thinking Skills, and Cognitive Load. The treatment population used simulated experiments, while the non-treatment sections performed traditional experiments. Comparisons were made using the Revised Two-Factor Study Process survey, Motivated Strategies for Learning Questionnaire, and the Scientific Attitude Inventory survey, using a Repeated Measures ANOVA test for treatment or non-treatment.

Keywords
Educational technology • Electronic learning • Physics education • Student experiments • Virtual laboratory

Introduction

Computer simulations and virtual laboratory science experiments have radically changed science education [1–3]. These laboratory experiments offer learners a more inquiry-based approach to science education following less constructed learning experiences that does not promote the prescribed outcomes of traditional science experiments [20]. As per the National Science Education Standards [4], Benchmarks for Science Literacy, the importance of inquiry-based science education throughout the United States is vital to progressive education, underscoring standards that address students devising scientific investigations incorporating Higher-Order Learning and promoting self-directed technology-centered learning. Traditional expository or teacher-centered labs echo, nearly verbatim, the prior learned topical scientific material. These labs require learners to conduct experiments with already known scientific outcomes, thus referred to as rote-memorization [5]. Laboratory goals of rote-based labs do not engage Critical Thinking in students [5] therefore; they do not always identify lab goals or regard the research process. Undergraduate lab science courses play a pivotal role in science curriculum, chiefly within the context of scientific inquiry ability and Critical Thinking [4, 6]. Virtual lab experiences, include science labs conducted via simulations, are intended to develop the skills vital for scientific research [7], as this modality allows for creating learning goals of Higher-Order Learning and Critical Thinking, not always possible in physical labs.

Higher-Order Learning and Cognitive Load

Higher-Order Learning Skills outlined in Bloom's Taxonomy [8] promote synthesis and evaluation of learned material. Critical Thinking Skills involve discerning rationale and

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analysis of material for breadth of knowledge [8]. Research has shown that visual symbolization, such as animations, is crucial to conveying scientific concepts [9]. Educational technology has been designed to coordinate visual cues and auditory procedures that guide learners through the construct of deeper understanding without taxation often associated with non-science learners during labs [4, 6]. Increased Cognitive Load builds learners' capability to comprehend more material at once by relying upon prior information, by using working memory, in union with multimedia technology, to create a learning environment coupling computer use with educational tools. Emerging educational technology, including simulations and virtual labs, can play a pivotal role in science education, offering learners the chance to practice true research methods that model scientific inquiry.

The Study

Review Stage

The purpose of this quantitative quasi-experimental study was to determine how the use of inquiry-based, virtual, and simulated science laboratory experiments increase learner perception of depth of learning via Higher-Order Learning Skills (HOLS), Critical Thinking (CT) skills, and Cognitive Load (CL) among learner participants at a 2-year community college. The predetermined instruments include: the Motivated Strategies for Learning Questionnaire (MSLQ) [10], the Scientific Attitude Inventory (SAI II) [11], and the Revised Two-Factor Study Process Questionnaire (R-SPQ-2F) [12]. The statistical analysis was conducted as to explore the relationships between use of inquiry-based simulated and virtual laboratory experiments and learner perceived increases in Higher-Order Learning Skills, Critical Thinking Skills, and Cognitive Load ability. The intention of this study was to investigate the increases of HOLS and CT skills in online and virtual science laboratory experiments, as compared to traditional face-to-face laboratory experiments. This study served to identify which course instructional delivery method will attain: perceived increased HOLS, CT skills, and increase CL capability within virtual laboratory science experiments.

The learners were separated into two pre-existing groups based on random selection of course section. The analysis was aimed at comparing laboratory format pre/post-lab surveys with learner perceived increases in Higher-Order Learning Skills (dependent variable), Critical Thinking Skills (dependent variable), and Cognitive Load (dependent variable) with respect to the two learner groups being treated or controlled (independent variable) controlling for the mathematical and scientific backgrounds of the learners (covariate) and the possible effects of computer usage skills will performing the simulated labs (covariate). The surveys were administered at the beginning and at the mid-point of the course, and it will determine how learners perceive an improvement or increase in their Higher-Order Learning Skills in science due to completing the course laboratory experiments. The rationale for administering the post-lab survey at the mid-point of the course is based on attrition rates for non-majors in the STEM laboratory courses. By surveying at mid-semester, the researcher had a more heterogeneous participant population. Whereas at the end of the semester, the population would be more homogenous consisting of the academically stronger students, thus biasing the data by showing an unequal mix of learners throughout the course.

Results

The results of the presented study are based on data collected during an academic year. A total of 150 learners participated in the study. Each learner provided informed consent to the collection of this data. All data are anonymized as to avoid any personally identifiable information.

Higher-Order Learning Skills

Higher-Order Learning Skills (HOLS) were assessed as to the extent in which they differed between simulated and virtual versus traditional laboratory experiments when comparing pre- and post-laboratory experiments? Results of the statistical analysis of the repeated measures indicated that the use of the simulation and virtual labs in the treatment group does increase the perception of comprehensive HOLS employment. The use of HOLS with simulations and virtual laboratory experiments consisted of two main subscales, that of motivation and learning strategies. The results showed that learners in the treatment (simulation and virtual laboratory experiment modalities) group had higher levels of HOLS usage and implementation (as measured by the MSLQ survey) than learners in the non-treatment (face-to-face on-campus laboratory experiment modalities) group. The findings from this research are that those learners in the treatment (simulation and virtual laboratory experiment modalities) group performed at a more advanced level than learners in the non-treatment group (face-to-face on-campus laboratory experiment modalities), is consistent with past research on the usage of simulation and virtual laboratory experiment within the science disciplines [13–16]. Metacognition involves the progression of self-correction and self-awareness of one's thinking processes and the application of heuristics [13, 17].

The results are significant in that they indicate the use of HOLS in a metacognitive capacity. The research findings denoted that learners are using more developed methods for scientific analysis through the use of Higher-Order Learning Skills. The inclusion of synthesis and analysis, within experimentation [6, 8], is evident that the progression of high-order processing and evaluation of learner material is ongoing. Furthermore, motivation and learning strategies were employed more often and in more substantial form from the treatment modality than from the non-treatment modality. The MSLQ assessed motivation levels between the treatment groups and the data showed greater use of motivation throughout the experiments and the overall scientific learning. Learning strategies were reflected in the use of Bloom's Taxonomy [8] that utilizes synthesis and analysis in situational learning experiences, such as laboratory courses. The estimated marginal means data (as shown in Fig. 1) shows that the treatment group increased their HOLS post-experiment.

The graph of estimated marginal means represented a comparison of unequal sample sizes between the treatment group and the non-treatment group. The relationship between the dependent variables depicted a computed average across the levels of within and between subject factors. The graph displays an interaction of the variables pertaining to the usage of virtual and simulated science labs' effect on Higher-Order Learning Skills.

These new findings can help to encourage science educators to include more simulation-based experiments and to author more inquiry-based labs. Previously, it was thought [4, 6] that these types of labs were inconclusive in their efforts to maintain strict scientific research principles and lacked the analytical prowess of traditional expository experiments. The data showed that this was not the case, based on the MSLQ ANOVA results that indicated learner motivation and analytical skills being higher than anticipated in the treatment group. The results will bolster the field of science education and educational technology as this new information will allow for more advanced research.

Critical Thinking Skills

Critical Thinking (CT) Skills were assessed as to the extent in which they differed between simulated and virtual versus traditional laboratory experiments when compared pre- and post-laboratory experiments. Results of the statistical analysis of the repeated measures indicated that the use of the simulation and virtual labs in the treatment group does increase the use of CT Skills. The use of CT Skills with simulations and virtual laboratory experiments consisted of two main subscales, deep learning and surface learning. The results showed that learners in the treatment (simulation and virtual laboratory experiment modalities) group had higher levels of CT Skill usage and implementation (as measured by the R-SPQ-2F survey) than learners in the non-treatment (face-to-face on-campus laboratory experiment modalities) group. The estimated marginal means data (as shown in Fig. 2) shows that the treatment group increased their CT Skills post-experiment.

The graph of estimated marginal means represented a comparison of unequal sample sizes between the treatment group and the non-treatment group. The relationship between the dependent variables depicted a computed

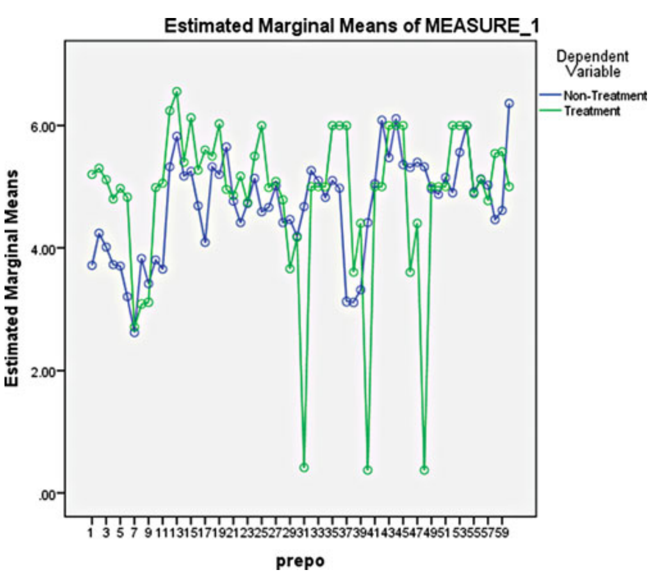

Fig. 1 Estimated marginal means for with-in subjects (pre/post-lab) MSLQ subscales

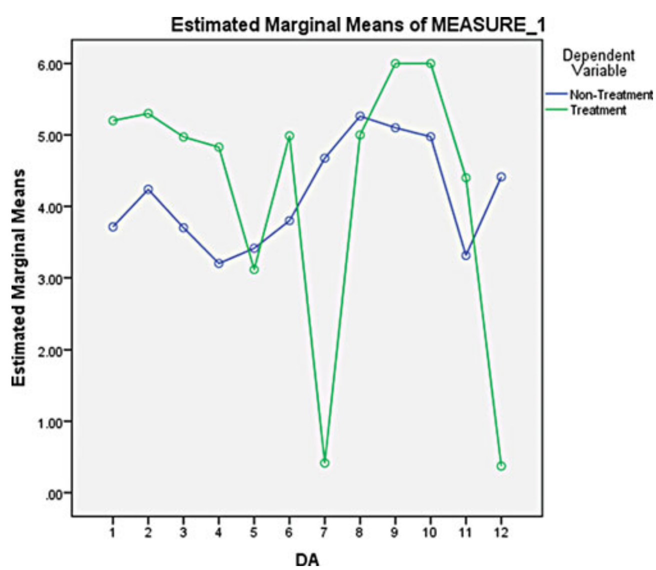

Fig. 2 Estimated marginal means for with-in subjects (pre/post-lab) R-SPQ-2F deep approach subscales

average across the levels of within and between subject factors. The graph displays an interaction of the variables pertaining to the usage of virtual and simulated science labs' effect on Critical Thinking Skills as it relates to deeper levels of learning. The levels of learning, both deep and surface level approaches, correspond to the treatment and non-treatment groups respectively.

The findings from this research are that those learners in the treatment (simulation and virtual laboratory experiment modalities) group thought more critically and analytically than learners in the non-treatment group (face-to-face on-campus laboratory experiment modalities), is consistent with past research on the usage of simulation and virtual laboratory experiment within the science disciplines [13–16]. According to Zoller and Pushkin [16], three components integral in science education within the domain of higher-order cognitive skills development include: problem-solving, Critical Thinking, and laboratory practice. The results are significant in that they indicate the use of CT Skills in a deep and surface learning capacity. The research findings denoted that learners are using more in-depth methods for scientific analysis through the use of Critical Thinking. The inclusion of critical thinking, within experimentation, is evident that the progression of synthesis and evaluation of learner material is ongoing [6, 8]. Furthermore, deep and surface learning strategies were employed more often and in more substantial form from the treatment modality than from the non-treatment modality. The data showed that this was not the case, based on the R-SPQ-2F ANOVA results that indicated learner depth of knowledge was higher than anticipated in the treatment group.

Cognitive Load

Cognitive Load (CL) capacity was assessed as to the extent in which they differed between the use of simulated and virtual laboratory experiments when compared pre- and post-laboratory experiments. Results of the statistical analysis of the repeated measures indicated that the use of the simulation and virtual labs in the treatment group does not statistically show great significance in the Cognitive Load. The effective use of Cognitive Load with simulations and virtual laboratory experiments was somewhat significant, as the within groups showed more efficient use of working memory than that of the between group results. The results showed that learners in the treatment (simulation and virtual laboratory experiment modalities) group had moderately higher levels of Cognitive Load usage and implementation (as measured by the SAI-II survey) than learners in the non-treatment (face-to-face on-campus laboratory experiment modalities) group. The findings from this research are that those learners in the treatment (simulation and virtual laboratory experiment modalities) group used similar levels cognitive load capabilities as did learners in the non-treatment group (face-to- face on-campus laboratory experiment modalities), is consistent with past research on the usage of simulation and virtual laboratory experiment within the science disciplines [13–16].

The results are moderately significant in that they indicate the use of Cognitive Load in a memory-based capacity. The research findings denoted that learners are using more working memory for scientific analysis through the use of Cognitive Load. The inclusion of working memory is evident, due to the amount of recall the learners had within the experiments. Furthermore, CL was employed often in the treatment modality than the non-treatment modality. These new findings can help to encourage science educators to include more simulation-based experiments that rely upon recall ability and the use of inter-connected knowledge from past learned material to form new connections. The data showed that CL ability, based on the SAI-II ANOVA results that indicated learner reliance on previously learned material was moderately higher than anticipated in the treatment group. The estimated marginal means data (as shown in Fig. 3) shows that the treatment group marginally increased their CL abilities post-experiment.

The graph of estimated marginal means represented a comparison of unequal sample sizes between the treatment group and the non-treatment group. The relationship between the dependent variables depicted a computed average across the levels of within and between subject factors. The graph displays an interaction of the variables pertaining to the usage of virtual and simulated science labs' effect on Critical Thinking Skills as it relates to surface levels of learning.

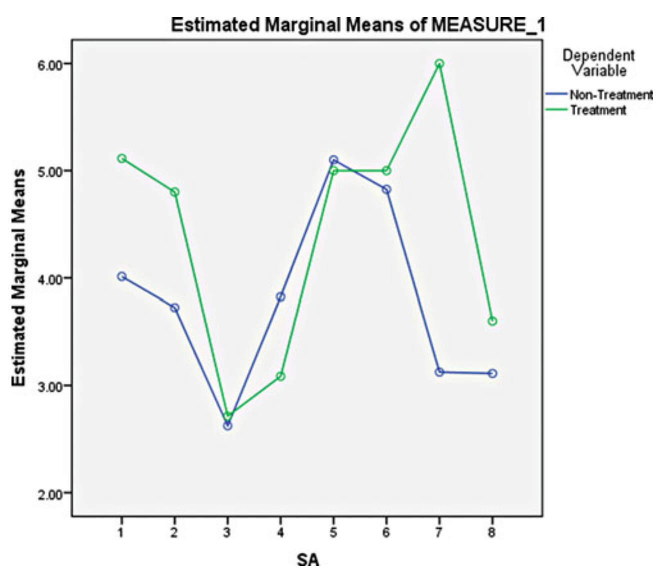

Fig. 3 Estimated marginal means for with-in subjects (pre/post-lab) R-SPQ-2F surface approach subscales

The levels of learning, both deep and surface level approaches, correspond to the treatment and non-treatment groups respectively. The treatment group showed a significant interaction for the with-in subject groups.

Summary and Conclusion

In this paper, the impact of virtual and simulation virtual laboratory experiments, on learning developing, Higher-Order Learning Skills (HOLS), Critical Thinking (CT) skills, and Cognitive Load (CL) capabilities, is studied. A pre/post survey methodology is introduced, as to distinguish learning events during laboratory experimentation. Statistical results are presented that show Higher-Order Learning Skills can be achieved as well as increased Cognitive Load ability in virtual and simulation laboratory learning environments. With the incorporation of these learning environments into General Science Study laboratory courses, learners may increase their knowledge base within defined course content areas more expressly directed at the science disciplines. The research study showed that, when utilized properly, simulation software and virtual laboratory experiments can facilitate an environment for learning that develops and fosters Critical Thinking and Higher-Order Learning. These variables will help to maintain or exceed Cognitive Load abilities; explicitly aimed at the scientific disciplines, scientific technology, and overall scientific awareness. Instructional and educational design of a course aids in the determination of whether a learner utilizes deep or surface learning through Higher-Order Learning Skills and Cognitive Load abilities [18]. Educators need to heed the use of simulations and virtual laboratory experiments in science courses so that their uses are based upon sound instructional theories and best practices [15, 19].

This study offered a discrete perspective for science educators with interests in simulation and virtual laboratory experiments and for educational technologists interested in creating these learning environments. Therefore, it is recommended that science educators and educational technology specialists in higher education fully examine the effectiveness of simulations and virtual laboratory experiments in science education. The requirements for learners in General Science Study laboratory courses is to master scientific concepts and engage in meaningful knowledge through learning approaches that can be used for a multitude of educational and career pathways. For the reason that many of these laboratory experiments will never be used by non-science major learners in their academic futures, the results of this research study may support the use of the educational technology instructional methodologies that are not "wet" laboratory based. The current research findings support the use of simulations and virtual laboratory experiment software in science laboratory experiments as long as science educators use the educational technology in a proper manner when designing and implementing instructional design planning for curricula. The results of this study will allow educators to identify that simulations and virtual laboratory experiments play an integral role in science education. Educational technology will only enhance the learning experience, not distract from the outcomes of the science curricula.

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