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A study on the effects of model-based inquiry pedagogy on students' inquiry skills in a virtual physics lab

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ABSTRACT

STEM integrated education has become the guiding principle of science education in many countries and a focus of research efforts. Developmental features of STEM education focus on using technology as a bridge to integrate multiple subjects. The focus on new technologies and practical applications are its major principles, and the aim of STEM education is to train a new generation of multi-skilled professionals capable of integrating knowledge from different fields of study to solve problems effectively. High school science courses based upon technological science models and science investigations have become the major means and methods for STEM education. For the past one hundred years, efforts of elementary education reforms worldwide have been focused on scientific inquiry. The development, utilization, evaluation, and revision of various scientific models and theories play a central role in scientific inquiry. Therefore, model-based inquiry would be crucial in improving the learning of science subjects. This study is based upon results from past MBI pedagogies research carried out by renowned academicians worldwide and incorporated a virtual physics lab developed for this study to create the MBI-VPL pedagogy method. Six main learning modules were designed, namely (1) topic introduction, (2) hands-on experiment, (3) virtual experiment, (4) team work, (5) actual applications, and (6) model adjustments. Results of experimental teaching showed that MBI and MBI-VPL pedagogy were more effective in developing student scientific inquiry skills compared to traditional methods, with significant improvements in the performance of process skills, comprehensive skills, learning attitude, communication skills, and reflection skills. The MBI-VPL pedagogy was able to introduce virtual physics experiment design and analysis, allowing students to gain in-depth practice of process skills, comprehensive skills, and reflection skills of scientific inquiry. Differences were also observed in the development of scientific inquiry skills during the experimental course between students of different genders. Boys performed better in process skills and comprehensive skills, while girls performed better in learning attitude and communications. The degree of student acceptance for the six major learning modules in the MBI-VPL model also showed that students tend to accept the use of process, comprehensive, and reflective skills of the virtual experiment.

1. Introduction

With the arrival of the information age and knowledge explosion, subjects of science, technology, engineering, and mathematics (STEM) have now been regarded as the theoretical basis and practical methods for achieving technological innovations. STEM professionals would determine the competitiveness of the country's industries in the global market. Many developed countries have realized the importance of STEM education and have made significant investments to improve the quality of STEM education in basic tertiary education to train an adequate number of professionals for future competition at the global level. Integrated STEM education has become primary directives and research topics in the science education policies of many countries. The American Framework for K-12 Science Education (NRC, 2011) and the Next Generation Science Standards based upon the foundations of STEM education represent some of the more famous examples. These policies and standards not only focus upon practical endeavors of both engineering and scientific fields, but also placed additional emphasis on the use of mathematics and computing in order to include engineering design and the interactions between engineering, science, technology, and society in the core concepts of STEM courses. These measures reveal the ambitious programs in

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integrating STEM subjects to develop science education in the United States.

Research on STEM topics involves studies on the effects of STEM education on students, schools, and classes, as well as detailed descriptions of STEM quality, analyses of how STEM education can help with the sustainable development of education programs, discussions on factors influencing student learning, and course set-up. Researchers (Morrison, 2006) have provided detailed descriptions on the qualities required of students undergoing STEM education, STEM institutions, and STEM classes between grades 6 and 12. Some researchers (Bybee, 2010) also studied the composition of STEM quality. He believed that STEM qualities include being able to understand concepts, having skills in operating various tools, and the ability to solve personal, social, and global issues related to STEM subjects. Therefore, STEM qualities would include the integration and mutual complementation of the four STEM subjects. Other researchers (James, 2009) studied STEM education and its relationship between concepts of sustainable education. These studies believe that sustainable development contents used in STEM activities can initiate waves of critical thinking in schools and communities and help provide new opportunities for career developments among educators. The STEM Center for Teaching and Learning of the International Technology and Engineering Educators Association (ITEEA) has developed an *Engineering by Design* model for K-12 education, where actual, topic-based learning environments were used which improved performance in STEM subjects in all students. The Maryland State Department of Education in the United States published the SE model that has integrated STEM education being used in the state. The model included five phases of participation, exploration, explanation, elucidation or extension and evaluation. In every phase of the SE model, clear division of labor was provided for the teachers and students. Teachers act as a guidance in learning, leading students into various topics, raising questions that need to be explored, and then initiating research. Research experience and conclusions obtained were then used to provide explanations to the questions raised while leading to understanding of the question. Researchers (Meyrick, 2011) have thus targeted these STEM courses to understand how they improve student learning. It was found that STEM education would use various activity-based learning modes to offer students a chance to conduct quick, in-depth learning. Students were encouraged to perform in-depth research in topics that interested them. The integration and links established between STEM courses and practical applications of acquired knowledge offered learners with different backgrounds equal opportunities in learning while developing the students' reasoning, critical thinking, innovative, and creative skills. Application of STEM subjects in daily lives would be mutually integrated with each other, and real problems tend not to be solely restricted to a particular subject. The shortcomings of subject-based education have become more obvious, and the directives of STEM development aimed to use technology as a bridge to integrate multiple subjects, with particular focus upon new technologies and their practical applications as the main principles. The main objective of STEM education would be to develop a new generation of multi-talented professionals capable of integrating multiple fields of science education in order to solve practical problems. For high school science courses, scientific models and scientific investigations based upon technological methods have become the dominant means of carrying out STEM education.

Scientific models are representations of how some aspects of the world work. Scientists create models in the forms of analogies, conceptual drawings, diagrams, graphs, maps, physical constructions, and computer simulations as a means of describing and understanding the organization of systems that range from cells to galaxies as well as natural processes that include evaporation and predator–prey relationships (Windschitl & Thompson, 2006).

Scientific inquiry has been a major focus for education reformation efforts worldwide during the last one hundred years. Every country has been encouraging students to develop scientific inquiry skills. The objectives of using realistic scenarios in scientific education are to help students acquire scientific knowledge and skills, understand the nature of science, and gain the necessary scientific upbringing and innovative mindset. New curriculum standards have clearly advocated scientific inquiry as a means of developing investigative skills and innovation among students. Three academic definitions have been offered for scientific investigation: (1) the work that scientists do; (2) the development of relevant scientific knowledge and mindset; (3) a process of teaching and learning. The *American National Science Education Standards* focused on all three definitions with its description of scientific inquiry as "the diverse ways in which scientists study the natural world and propose explanations based on the evidence derived from their work. Inquiry also refers to the activities of students in which they develop knowledge and understanding of scientific ideas, as well as an understanding of how scientists study the natural world (National Research Council [NRC], 1996)."

Current literature suggested that models and modeling are important parts of doing science, with models playing a number of key roles in scientific inquiry (Khine & Saleh, 2011). Four distinct functions have been identified for scientific models: discovery, development, evaluation, and exposition (Cosgrove, 1995; Holyoak & Thagard, 1996, 1997). Discovery occurs when the model contributes to the formation or generation of a new knowledge or the formulation of a hypothesis (Ganguly, 1995; Johnson-Laird, 1989; Stavy & Tirosh, 1993). When a hypothesis or discovery has been made, the model may then be used to further its development, either from a theoretical or from an experimental perspective (Veenman, Elshout, & Busato, 1994). As the model undergoes development, it must be tested as well, and so models play an important role in the evaluation of a hypothesis, and in evaluating arguments for or against the hypothesis. Finally, models are commonly used for exposition to explain hypotheses or theories to others (Khine & Saleh, 2011).

Model-based inquiry (MBI) is an emerging instructional strategy gaining acceptance among science educators (Neilson, Campbell, & Allred, 2010). MBI is a process in which students develop questions and procedures, carry out experiments, and generate and communicate conclusions in an effort to explore various phenomena and construct and reconstruct models based upon results achieved by scientific investigations (Oh & Oh, 2011). Model-based reasoning is a cornerstone of every discipline to some degree (Derry, 1999; Frigg & Hartmann S., 2006; Giere Ronald, 1988; Gilbert, Boulter, & Elmer, 2000), as all scientific inquiries in various disciplines have been guided using models developed by scientists to offer explanations for data and to further explore the mysteries of nature. The development, use, assessment, and revision of models and its explanations play a central role in scientific inquiry and should be a prominent feature of science education (Passmore, Stewart, & Cartier, 2009).

With the development of various technical theories in applied pedagogy and the appearance of virtual simulation technologies (Jou & Wu, 2012), a new approach of virtual simulation has become available for the teaching of physics. Virtual simulation is a technology based upon simulation principles, information, system analysis, design and other techniques (Mäkitalo, Weinberger, Häkkinen, Järvelä, & Fischer, 2005). It is an integrative technical field that utilizes computers and various physically responsive tools to create model systems for conducting experiments in an actual or imaginary system (Clark, D'Angelo, & Menekse, 2009). Virtual simulations performed using computers can be applied to