INTEGRATING INFORMATION TECHNOLOGY AND SCIENCE EDUCATION FOR THE FUTURE: A THEORETICAL REVIEW ON THE EDUCATIONAL USE OF INTERACTIVE SIMULATIONS

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Abstract

Information technologies offer potentially powerful new environments for communicating ideas in science education. This paper critically surveys the research literature to explore ways in which secondary school teachers are using interactive simulations to enhance their students’ scientific literacy and enable their students to meet science learning goals. The Australian National Curriculum for Science notes that: “Digital aids such as animations and simulations provide opportunities to test predictions that cannot be investigated through practical experiments in the classroom and may enhance students’ understanding and engagement with science.” Interactive simulations as ‘exploratory’ applications will be integrated with science education in this paper. The relationship between interactive simulation and science education will be discussed followed by introduction. And then, cognitive theory and related assumptions will be presented as theoretical ‘lenses’ as well as design principles which support the applications of interactive simulations in educational instructions. After critical analysis of the related studies focused on science education with information technology tools, this paper concludes with a brief discussion of future research directions in the field.

Introduction

Students’ science achievement varies internationally, but a lack of interest in science is common (Project Tomorrow and PASCO Scientific, 2008). Indifference or even hostility toward science could constrain students’ scientific learning and even the qualifications of scientists and technical workers in the future. Traditional science instructions such as discrete science fact rote-learning, teacher-centered lectures, “cookbook” laboratory activities and summative tests don’t promote students achievements in science learning, ironically serve to destroy students’ innate curiosity about the world of science. In 2005, National Research Council argued that integrating science education with technology is the promising approach for supporting students’ learning in science and meeting educational goals which include (1) inspiring students’ engagement with learning, (2) supporting them to develop conceptual understanding and science process skills, (3) helping them understand the nature of science and scientific discourse, and (4) supporting their developing identification with the world of science (National Research Council, 2005). The Australian National Curriculum for Science (ACARA, 2010) notes that: “Digital aids such as animations and simulations provide opportunities to test predictions that cannot be investigated through practical experiments in the classroom and may enhance students’ understanding and engagement with science.” This proposed research contends integrating interactive simulations into science education for promoting students’ scientific literacy and meeting science education goals.

Interactive Simulations and Science Education for the Future

Interactive simulations as external visual representations of dynamic systems of scientific phenomena are
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considered to be ‘exploratory’ applications (Kozma & Russell, 1997, 2005). Interactive simulations provide students new approach to learn science. Students can observe scientific elements, manipulate experimental parameters, test hypotheses, and get feedbacks in a timely way (Gilbert & Boulter, 1998; Plass, Homer, & Hayward, 2009; Taylor, Renshaw, & Jensen, 1997). And interactive simulations make the invisible scientific phenomena and processes visual. This way is considered to facilitate students’ deeper learning (Kozma & Russell, 1997, 2005). Linn et al. (2010) argued that interactive simulations act as intermediate models that make students’ learning much more readily apparent, supporting students to explore and formulate invisible phenomena, build up relationships between abstract representations of scientific phenomena and invisible processes and develop their own conceptual understanding.

This paper defines interactive simulations as dynamic computer-based models which can help students observe invisible scientific phenomena and allow students to manipulate experimental sets and accomplish science education goals. Five features of interactive simulations including (1) high engagement, (2) interactivity, (3) hypothesis testing, (4) instructional scaffolding and (5) timely feedback will be as the criteria for choosing the specific interactive simulation in the further study.

In 2005, National Research Council proposed the goals of science education involving (1) develop students’ conceptual understanding, (2) foster their science process skills, (3) help them to understand the nature of science, (4) teach them the unique conventions of scientific discourse, (5) maintain motivation for science learning, and (6) support students’ self-identification as scientific thinkers when in engaging in investigative practices (National Research Council, 2005). Based on the proposed six goals and the functions of interactive simulations, this paper summarizes four dimensions on order to integrate information technology into science education for the future as presented below.

- Dimension 1: Sparking motivation to learn science;
- Dimension 2: Developing conceptual understanding;
- Dimension 3: Promoting science process skills and understanding of the nature of science;
- Dimension 4: Developing students’ skills in scientific discourse and argumentation and identification with science learning.

This framework is not specific to the context of interactive simulations, of course: it is a general way of attending to the different goals and emphases within science education that go to make up an expanded notion of scientific literacy. It is by attending to each of these dimensions at a high level that science education can fulfill its mandate of preparing citizens for scientifically-informed engagement in the significant challenges that the future will present for society.

Why Study Interactive Simulation?

The development of cognitive theory promotes the educational application of interactive simulations. Principles underpinned by specific assumptions in turn make interactive simulations a promising visualization tool for advancing students’ science learning (Scalise, 2009).

Cognitive theorists advocate the notion that there is a link between external information representations and internal information – mental models. The mental model is like an internal simulation thought process (selecting data, hypothesizing, conducting, making conclusion et al.) of the external world which is constructed by a person’s intuitive perceptions, analogies or acts of imagination. ‘Mental Model-Based Teaching and Learning’ (Gobert, 2000) and the use of interactive simulations for scaffolding learning (Gobert, 2005) are theoretical perspectives on why interactive simulations – due to their mapping to students’ mental models and affordances for students to test and elaborate those models – are likely to be effective tools for learning. Buffler suggests that mental models offer a site for mediation between mental images and propositional representations of knowledge. In science education, high level theories and invisible objects are not described directly by instructors. Mediation is needed to match the mental model to the canonical scientific concepts and support students in learning such high level theories in relation to real world phenomena. In comparison with traditional instructional approaches such as text-based
materials, interactive simulations are used to provide sites for the kind of mental mediation and manipulation of students’ internal models of phenomena and concepts that Johnson-Laird (1983) described. When students’ mental models agree with the model of the real world implied by the interactive simulation, students obtain opportunities to foster the development of their metavisual capacity which is one important means of distinguishing between expert scientists and novice scientists (Buffler, et al., 2008). Characteristics of interactive simulations such as a focus on causal relations, more active learning and mutual student support mean that they offer very effective ways to improve metavisual capacity and to build deeper comprehension.

Also, cognitive load theory (Sweller, van Merrienboer, & Paas, 1998) contend human cognitive architecture. Furthermore, it assumes that a limited ‘buffer’ of short term memory (also called working memory) interacts with the effectively unlimited long term memory (Cook, 2006). It asserts that learning will be impaired by the presentation of overwhelming levels of novel information which must be processed in working memory (de Jong, 2010; Sweller, et al., 1998). Working memory is limited in capacity and duration, limiting its ability to further process novel information and retrieve prior knowledge. Working memory typically stores seven to eight elements but manipulates only two to four elements through sensory memory. Within about 20 seconds novel information will be lost if people don’t process it more deeply through rehearsal (van Merriënboer & Ayres, 2005). However, retrieval from long term memory doesn’t have these limitations (Ericsson & Kintsch, 1995; Paas, Renkl, & Sweller, 2004; Sweller, 2003). Presentations combining visual and verbal information (e.g. as graphs, animations, simulations et al.) have been widely used for supplementing (Cook, 2006) or even replacing traditional instructional materials. Cognitive load theory is no longer limited to traditional classrooms but has turned to the design of multimedia representations (Mayer & Moreno, 2002, 2003) as well as active learning environments for computer-based collaborative learning (van Bruggen, Kirschner, & Jochems, 2002).

In addition, dual coding theory proposed by Paivio (1986) noted that there are two processing systems in people’s cognitive systems: a cognitive-verbal system and a non-verbal system. The former emphasizes learning though language-like processing such as words in spoken or printed text; the latter includes emotions and visual representations such as pictures, visual simulations and other visualization tools. Rieber (2002) claimed that visual stimuli such as pictures offer greater support than verbal stimuli such as words for encoding and retrieval of information. Based on dual coding theory (J. M. Clark & Paivio, 1991; Mayer & Anderson, 1991; Paivio, 1986), cognitive load theory and constructivist learning theory, Mayer and Anderson (1992) presented three basic assumptions to explain how people learn concepts and principles in multimedia situations: dual channel, limited capacity, and active processing. Later, multimedia principle, contiguity principle, coherence principle, modality principle, redundancy principle, interactive principle, signaling principle and personalization principle proposed by Mayer (2001). These eight principles of multimedia learning were derived from numerous research findings and intended to address and support the learning of difficult concepts and principles.

Cognitive theory and a number of assumptions embedded in this theory provide theoretical ‘lenses’ as well as some design principles to support the development and educational use of interactive simulations. Instructional design principles (e.g. multiple representations, dual-mode presentations, narration, split-attention material, redundant material, animation, material with interacting elements, and instructional guidance) based on different assumptions of cognitive theories have been supporting students’ learning (Cook, 2006). In terms of the proposed four learning goals, related studies on effectiveness of science education with interactive simulations will be presented in the following part.

Implementations of Science Education with Interactive Simulations

Goal 1: Sparking Motivation to Learn Science

‘Motivation’ in this context means that students are interested in persisting in order to learn about scientific phenomena in the natural and physical world because they obtain excitement and interest from
the learning journey (Honey & Hilton, 2010).

Analysis of many studies shows that some students who view science as boring find using simulations in the classroom unexpectedly interesting (Ketelhut, 2007). Results of national surveys showed that K-12 students enjoy learning science through interactive simulations (Partnership for reform in science and Mathematics, 2005; Project Tomorrow and PASCO Scientific, 2008). Synthesizing findings over the past thirteen years, many studies support the use of interactive simulations to motivate students in science (D. B. Clark, Nelson, Sengupta, & D'Angelo, 2009).

**Goal 2: Developing Conceptual Understanding**

The use of interactive simulations to support students’ conceptual development is now commonplace. Conceptual understanding emphasizes how scientific concepts, models and facts are generated and how to understand, explain and use them in new settings instead of memorizing (Honey & Hilton, 2010).

Evans, Yaron, and Leinhardt (2008) conducted a controlled study comparing interactive simulation laboratories and other instructional approaches. Forty five undergraduate students participated in the same classes on stoichiometry. Twenty one of them took the course online and the other 24 students took the course in a text-only mode. Analyzing proctored tests of stoichiometry concepts and procedures, Evans, Yaron, and Leinhardt (2008) found significant gains in test scores for the online group over the text-only group. Regression analysis of posttest scores showed that nearly 40 percent of the variation in posttest scores of the online group was related to treatment. Although the participants were college freshmen, the result supports the implementation of interactive simulation to build up concepts in science classes.

Studies found that some interactive simulations made students confused (D. B. Clark, et al., 2009; Coll & Treagust, 2001; Ingham & Gilbert, 1991; Xie & Tinker, 2006) and researchers have conducted research to seek solutions to this issue. Interactive simulations show substantial, robust gains on conceptual learning when students obtain certain kinds of instructor guidance (Boulter & Gilbert, 2000; Huddle, White, & Rogers, 2000).

Researchers indicate that learning through simulations or based-simulation technology can enhance students’ deep understanding of scientific concepts (de Jong, 2009; Quellmalz, Timms, & Schneider, 2009). Interactive simulations are most effective when placed within a broader curriculum unit and supported by scaffolding and teacher support. There is still considerable research effort needed into these essential contextual features that can enhance or vitiate the effectiveness of interactive simulations for conceptual development.

**Goal 3: Promoting Science Process Skills and Understanding of the Nature of Science**

One of the challenges in science education is to engage students in inquiry or scientific investigative process skills in the classroom. Interactive simulations offer new affordances for enhancing students’ science inquiry (Jacobson, 2004).

A study on a virus simulation conducted by Klopfer, Yoon, and Um (2004) found that the genetic inheritance simulation helped 5th and 7th graders develop understanding of several primary science processes such as testing and patterns of hypothesis, in addition to promoting their understanding of several principles and concepts.

Buckley, Gobert, and Horwitz (2006) reported the relationship between the development of science process skills and understanding of concepts in simulation-based classroom. Students used a software system linking simulations to a genetics unit in text and wrote logs when they interacted with the instructional system to solve science process tasks. In analysis of students’ pre- and post-tests, researchers argued that developing understanding of science processes helped students’ conceptual understanding.

More recently, Klahr, Triona and Williams (2007) conducted a comparative study on a Physics unit. Fifitsix seventh and eighth graders used a ‘Virtual Mousetrap Simulation’ and a hands-on activity. Analysis of observations and posttests indicated that students achieved significant gains in their understanding of causal factors.
Goal 4: Realizing Scientific Discourse and Argumentation and Identification with Science Learning

Scientific discourse includes scientific language – including numbers and symbols – through which the science community shares norms, experiments, and results, and students are encouraged to correctly use scientific discourse (Honey & Hilton, 2010). When they engage with science and use scientific discourse, students think about whether they are acting as science learners and whether they would like to develop an identity and contribute to science.

A high school study focused on ‘ChemSense’ to investigate the impact of simulation-based curriculum on students’ deep conceptual understanding in the web-based laboratory (Michalchik, 2008). Over the period of two weeks, students constructed scientific discourse and became more confident in science learning when they used ChemSense representations. Students’ discourse moved from features of the experiments to the analysis of molecular entities and scientific processes. Thus, scientific discourse increased in the classroom and students’ test scores showed gains and outperformed students in a control group.

Future Research

There are many challenges involved in exploring the effectiveness of interactive simulations for enhancing students’ achievement in science learning goals. Firstly, we lack research methodology to motivate the educational use of interactive simulations. New research methods that both determine empirically the role of interactive simulations and provide detailed descriptions of the quality of interactive simulation in science learning must replace marginal pre- and post-test measures and imprecise anecdotal self-reports. More rigorous research methods that keep up to date with rapid technological developments and draw on well-elaborated theoretical frameworks will be required in order to develop an approach to implementation that is more strongly based in the evidence rather than in ad hoc adoption of technologies by teachers who are enthusiasts. This is not to discourage or disparage that community of enthusiasts, but to note that it does not in itself provide a strong research base for broader implementation. Secondly, the scale and scope of the studies impede research. Many researches are conducted in one or two classrooms rather than on a larger scale. Thinking about variations of interactive simulations, different teaching approaches, the school context and home context, students’ prior science and other learning experiences including age, sex, academic ability and a plethora of other variables makes research that can yield broad recommendations for practice difficult to develop. Thirdly, technologists tend to focus on design, with less attention to underlying principles of scientific theories. Students no longer think of science as related to the daily life and their own experiences (Cavallo & Laubach, 2001; Cohen, 2003; Gibson & Chase, 2002; Ma & Wilkins, 2002). The design of effective interactive simulations should pay attention to real world and be based on cognitive theories and principles. Last but not least, broader implications for policy-makers and society in general, as providing the computer infrastructure and (more important but often neglected) teacher professional development and technical support, should realize the potential of interactive simulations in science education.

Cooperation between educational researchers, cognitive scientists, technology designers and policy-makers is critical to integrate interactive simulations with science education. With the cooperation of each community, we are now conducting a research project named AIIS project (Fan & Geelan, 2012) which integrates interactive simulation into senior secondary physics classroom in Mainland China. The findings will contribute to develop high-quality science education and enhance the scientific literacy of students’ and future citizens.

Integrating interactive simulations into science education by no means offers a panacea for science learning. However, they represent a new song in the repertoire, a new tool in the toolbox, of science teaching, and complement the range of other strategies and approaches available to science teachers. More studies are well worthwhile further investigation.
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