Computers & Education 68 (2013) 253–265

Contents lists available at SciVerse ScienceDirect

Computers & Education

journal homepage: www.elsevier.com/locate/compedu

Examining the effect of the computational models on learning performance, scientific reasoning, epistemic beliefs and argumentation: An implication for the STEM agenda

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A R T I C L E I N F O

Article history:
Received 11 March 2013
Received in revised form
10 May 2013
Accepted 11 May 2013

Keywords:
Modelling
Computational experiment
Reasoning abilities
Epistemological beliefs
Argumentation

A B S T R A C T

Computational experiment approach considers modelling as the essential feature of Inquiry-Based Science Education (IBSE) where the model and the computer take the place of the "classical" experimental set-up and simulation replaces the experiment (Landau, Páez, & Bordeianu, 2008).
Modelling, as a pedagogical tool, involves the model construction, the exploration of model characteristics and the model application to a specific problem, resembling authentic activities of scientists and mathematicians (Herbert, 2003). Jonassen and Strobel (2006) state that in addition to modelling domain knowledge, learners can apply modelling skills in different ways: by modelling domain knowledge, by modelling problems (constructing problem spaces), by modelling systems and by modelling semantic structures. The purpose of this study was to explore the effects of the Computational Experiment Mathematical Modelling (CEMM) approach on University students': a) reasoning abilities, b) learning performance, c) epistemological beliefs, and d) argumentation. Students worked in a learning environment which contained applications in Physics created by the author and all of them were based on mathematical models, as the model was considered as the fundamental unit of instruction (Hestenes, 1999). Fifty (50) pre-service primary school university students participated in this project and results indicated a strong relationship between students' learning performance, performance in the scientific reasoning abilities test, epistemic beliefs and the ability to use arguments during computational experiments. This paper suggests an implementable integration strategy that uses mathematical models for physics phenomena that are developed using algorithms, aiming to deepen students' conceptual understanding and scientific reasoning. After completing the course, the mechanics baseline test (MBT) and a test on Heat were administered. The results indicated that there was a significant difference in problem-solving skill test mean scores, as measured by the MBT, and the test on Heat among concrete, formal and postformal reasoners. Overall, this study provides evidence that scientific reasoning has a strong impact to learning performance, scientific reasoning, epistemological beliefs and argumentation while the methodology of the Computational Experiment provides essential tools to students to implement Inquiry based scenario. Students developed their scenarios using an open source repository using the computational experiment approach and created their experiments using the Argument-Driven Inquiry (ADI) laboratory approach.
Results have implications for the effectiveness of the computational experiment as a methodology to be included in the STEM agenda.

1. Introduction

1.1. *Inquiry and modelling in science education*

The field of science education research is concerned with the development of high-level skills like concept construction, modelling, problem solving, cognitive–metacognitive skills and involvement in scientific/conceptual processes (Halloun, 2006).

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http://dx.doi.org/10.1016/j.compedu.2013.05.015

Inquiry based learning has officially been promoted as a pedagogical method for improving science learning in many countries (Bybee, Trowbridge, & Powell, 2008) and can be defined as "the intentional process of diagnosing problems, critiquing experiments, distinguishing alternatives, planning investigations, researching conjectures, searching for information, constructing models, debating with peers, and forming coherent arguments" (Bell, Hoadley, & Linn, 2004). Inquiry is also considered as a way to implement the scientific method in schools (Levy, Little, McKinney, Nibbs, & Wood, 2010).

Science and Mathematics educators have long recognized the importance of modelling in understanding scientific and mathematical phenomena (Jonassen & Strobel, 2006; Lehrer & Schauble, 2000). Modelling is an essential cognitive skill for meaning-making in all disciplines. In addition to modelling domain knowledge, learners can apply modelling skills in different ways: by modelling domain knowledge, by modelling problems (constructing problem spaces), by modelling systems, and by modelling semantic structures. Models are also considered as crucial pedagogical tools for meaningful and efficient learning of science as model structure converts the heap into a coherent conceptual system.

1.2. *The computational experiment*

In recent years the sciences and other disciplines have come to rely on computational models as important tools in many types of inquiry based teaching approaches. The term computational model refers to representations of physical or other systems that are first expressed mathematically as models and then implemented in the form of computer programs or programming languages. A computational model can be viewed as a representation of a function that produces values of outputs, when executed for specific values of inputs. According to Sloot (1994) computational science (CSE) aims to create reliable computational experiments. Sloot (1994) identifies three major phases in the process of the development of a computational experiment (CE): 1) The Modelling phase. The first step to simulation is the development of an abstract model of the physical system under study. 2) The Simulation phase. Mathematical methods are developed that make the underlying physical models discrete and consider the time dependence of the state variables of the system. A numerical analysis method is employed at this phase in order to end up with an algorithm. 3) The Computational phase. In this phase we concentrate on the mapping of the simulation techniques to source code, which implements the algorithm using either interpreted software (e.g. Mathematica) or a programming language (e.g. Java). Computational Science can be considered as a third independent scientific methodology (the other two are the theoretical science and the experimental science) and has arisen over the last twenty (20) years and shares characteristics with both theory and experiment, while it demands interdisciplinary skills in science, mathematics and computer science <http://web.mst.edu/∼vojtat/teaching/teaching.html> (Retrieved 19 February, 2013). According to Landau et al. (2008) computational science focuses on the form of a problem to solve, with the components that constitute the solution separated according to the scientific problem-solving paradigm: a. Problem (from science), b. Modelling (mathematical relations between selected entities and variables), c. Simulation Method (time dependence of the state variables, stochastic processes like Monte Carlo), d. Development of algorithm, e. Implementation of the algorithm (using Java, Mathematica, Fortran etc) and f. Assessment and Visualization through exploration of the results and comparison with real data. In this framework, being able to transform a theory into an algorithm requires significant theoretical insight, detailed physical and mathematical understanding as well as a mastery of the art of programming (Psycharis, 2011). Computational experiments complement analytical theories and real experiments by providing a tool for explaining what was observed and predicting what will happen. Computational Models are also considered as a pillar of science education—in parallel to mental and physical models—if appropriate user interfaces are provided to make them accessible to every student (Xie et al., 2011). In order to describe discovery/inquiry based learning as a research process, Shunn and Klahr (1995) and Klahr and Dunbar (1998) introduced the hypothesis and the experimental spaces in order to describe the discovery/inquiry based learning as a search process. In their model the hypothesis space contains all rules and variables describing the specific domain, while the experiment space consists of all experiments that can be implemented within this domain. Psycharis (2011) extended these spaces in order to include the computational experiment approach and suggested three spaces for the computational experiment, namely:

1. The hypotheses space, where the students in cooperation with the teacher, decide, clarify and state the hypotheses of the problem to be studied, as well as the variables and the concepts to be used as well as the relations between the variables.
2. The experimental space, which includes the model and the simulation for the problems under study. In this space the learners are engaged in the scientific method writing models according to the interaction laws that govern the phenomenon.
3. The prediction space, where the results, conclusions or solutions formulated in the experimental space, are checked through the analytical (mathematical) solution as well as with data from the real world.

Developing inquiry-based learning environments with the integration of computational science seems to be an essential research issue in science education. Bell, Urhahne, Schanze, and Ploetzner (2010), identified nine main science inquiry processes supported by different computer environments that could be used in Inquiry-Based Science Education (IBSE), namely: orienting and asking questions; generating hypotheses; planning; investigating; analyzing and interpreting; exploring and creating models; evaluating and concluding; communicating; predicting. The nine inquiry tools of Bell et al. (2010) are closely related to the essential features of Inquiry (Assay & Orgill, 2010), namely: Question (the learner engages in scientifically oriented questions), Evidence (the learner gives priority to evidence), Analysis (the learner analyses evidence), Explain (the learner formulates explanations from evidence), Connect (the learner connects explanations to scientific knowledge) and Communicate (the learner communicates and justifies explanations). We notice that the role of modelling is essential both as an inquiry tool and as a feature of inquiry. The fundamental component of the computational experiment (CE) is the development of models, which makes it strongly connected to inquiry processes. Our proposal integrates inquiry approach and computational experiment (CE) through the interconnection of the CE spaces, namely the hypotheses space, the experimental space and the prediction space with the essential features of inquiry and the inquiry tools.

In Table 1 below, we present the correspondence between the spaces of the CE and the features and the tools of inquiry.