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Assessment of scientific reasoning: The effects of task context, data, and design on student reasoning in control of variables

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ABSTRACT

Scientific reasoning is an important component under the cognitive strand of the 21st century skills and is highly emphasized in the new science education standards. This study focuses on the assessment of student reasoning in control of variables (COV), which is a core sub-skill of scientific reasoning. The main research question is to investigate the extent to which the existence of experimental data in questions impacts student reasoning and performance. This study also explores the effects of task contexts on student reasoning as well as students' abilities to distinguish between testability and causal influences of variables in COV experiments. Data were collected with students from both USA and China. Students received randomly one of two test versions, one with experimental data and one without. The results show that students from both populations (1) perform better when experimental data are not provided, (2) perform better in physics contexts than in real-life contexts, and (3) students have a tendency to equate non-influential variables to non-testable variables. In addition, based on the analysis of both quantitative and qualitative data, a possible progression of developmental levels of student reasoning in control of variables is proposed, which can be used to inform future development of assessment and instruction.

1. Introduction

As science continues to be fundamental to modern society, there is a growing need to educate on the process of science along with science content. That is, within science courses there is greater emphasis on the general reasoning skills necessary for open-ended scientific inquiry (Bybee and Fuchs, 2006). This is reflected in the *Framework for K-12 Science Education* (NRC, 2012), the basis for the Next Generation Science Standards (NGSS), which clearly lay out the scientific processes and skills that students are expected to learn at different grade levels. For example, students as young as middle school are expected

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to learn how to analyze evidence and data, design and conduct experiments, and think critically and logically in making connections between data and explanations. These skills, often broadly labeled as scientific reasoning skills, include the ability to systematically explore a problem, formulate and test hypotheses, control and manipulate variables, and evaluate experimental outcomes (Bao et al., 2009; Zimmerman, 2007).

Physics courses provide ample opportunities to teach scientific reasoning (Boudreaux, Shaffer, Heron, & McDermott, 2008), and the American Association of Physics Teachers has identified goals for physics education that reflect this idea; including experience in designing investigations, developing skills necessary in analyzing experimental results at various levels of sophistication, mastering physics concepts, understanding the basis of knowledge in physics, and developing collaborative learning skills (AAPT, 1998). To better achieve these goals, an increasing number of inquiry-based physics curricula have been designed with the focus on helping students learn both science content and scientific reasoning skills. A non-exhaustive list of such courses includes Physics by Inquiry (McDermott, Shaffer, & The Physics Education Group at the University of Washington, 1996), RealTime Physics (Sokoloff, Thornton, & Laws, 2004), ISLE (Etkina and Van Heuvelen, 2007), Modeling Instruction (Wells, Hestenes, & Swackhamer, 1995), and SCALE-UP (Student-Centered Activities for Large Enrollment Undergraduate Programs) (Beichner, 1999). A common emphasis of these reformed curricula is to engage students in a constructive inquiry learning process, which has been shown to have a positive impact on advancing students' problem solving abilities, improving conceptual understanding, and reducing failure rates in physics courses. Most importantly, the inquiry-based learning environment offers students more opportunities to develop reasoning skills; opportunities otherwise unavailable in traditionally taught courses (Beichner and Saul, 2003; Etkina & Van Heuvelen, 2007).

Among the different components of scientific reasoning, control of variables (COV) is a core reasoning skill, which is broadly defined as the ability to scientifically manipulate experimental settings when data is collected to test a hypothesis. In such manipulations, certain variables are kept constant while others are changed. In teaching and learning, both the recognition of the need for such controls and the ability to identify and construct well controlled conditions are the targets of assessment and instruction.

The COV ability has been extensively researched in the literature (Chen and Klahr, 1999; Kuhn, 2007; Kuhn and Dean, 2005; Lazonder and Kamp, 2012; Penner and Klahr, 1996; Toth, Klahr, & Chen, 2000). COV is an important ability needed in almost all phases of scientific inquiry such as variable identification, hypothesis forming and testing, experimental design and evaluation, data analysis, and decision making. The existing research reveals a rich progressive spectrum of sub skills under the generally defined COV ability; from the ability to identify simple configurations of COV conditions to the more complex multi-variable controls and causal inferences from experimental evidence.

For example, in research involving elementary students, Chen and Klahr engaged students in simple experiments involving only a few variables (Chen and Klahr, 1999). Students in second through fourth grade were presented with a pair of pictures and asked to identify whether they showed a valid or invalid experiment to determine the effect of a particular variable. The researchers found that elementary students as young as second grade were not only capable of learning how to identify COV experiments, but also were able to transfer their COV knowledge when the learning task and the transfer task were the same. In studies of third and fourth graders, Klahr and Nigam found that students were able to design unconfounded experiments and make appropriate inferences after direct instruction, although performance was not always consistent (Klahr and Dunbar, 1988).

More complex tasks were used in the studies by Penner and Klahr (1996), in which middle school students were presented with multiple variables in different contexts such as those involving ramps, springs, and sinking objects. For the context involving sinking objects, Penner and Klahr (1996) probed student understanding of multi-variable influence by asking what combination of variables would produce the fastest sinking object. They found that younger children (age 10 years) were more likely to design experiments which demonstrated the correctness of their own personal beliefs; whereas older students (12 and 14 years old) were more likely to design unconfounded experiments and tended to view experiments as a means of testing hypotheses.

The work of Kuhn focused on higher-end skills regarding students' abilities in deriving multi-variable causal relations (Kuhn, 2007). In one study, fourth-graders used computer software to run experiments related to earthquakes (and ocean voyages). The context of this study enabled more variables to be included than in the previously mentioned studies. In addition, within this study students were asked to determine whether each variable was causal, non-causal, or indeterminate. A number of findings were observed: students were better able to identify a causal variable rather than a non-causal variable. Students did not always realize that one can test something even if it does not influence the result. In addition, although students could progress in learning COV skills, they continued to struggle when handling multivariable causality. For example, students sometimes described what they thought would be the cause of an outcome using descriptors that did not match their experimental results. There were also cases in which students described a certain material as being necessary even though it was not mentioned during experimentation. Kuhn concluded that students could correctly design experiments but did not have a good method for handling multivariable causality (Kuhn, 2007).

More recent work by Boudreaux et al. involves the study of COV abilities of college students and in-service teachers, in which they identified three distinct COV abilities at progressing levels of complexity (Boudreaux et al., 2008). The first and simplest level was the ability to design experimental trials. Students were given a scenario with a specific set of variables and were asked to design an experiment that could test whether a particular variable influenced the outcome and explain their reasoning. The second level was the ability to interpret results when the experimental design and data warranted a conclusion. Students were presented with a table of different trials and data from an experiment and asked whether a given