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Undergraduate students demonstrate common false scientific reasoning strategies

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ABSTRACT

American education is failing to fill the growing demand for science, technology, engineering, and mathematics (STEM) graduates. The lack of critical reasoning skills may be a causal factor in student attrition from STEM majors. Our objective in this study was to discover and describe common false strategies used by undergraduate students during the scientific reasoning process. Each of these false strategies is described, with accompanying examples from student responses, to illustrate the thinking patterns. We defined targeted areas for instruction that can lead to better performance, greater academic self-confidence, and increased retention in STEM degrees. Understanding how students think through problems and where they are making mistakes facilitates the creation of specialized programs to correct these false reasoning strategies and increase the scientific reasoning ability of students.

1. Introduction

Currently, only 40% of students who enter college with the intent to pursue a STEM degree actually do so (PCAST, 2012). STEM degrees comprise less than 16% of Bachelor's degrees awarded by American colleges (NCES, 2009). Over twenty-six years ago, Project 2061 (AAAS) established a goal to advance science, math, and technology learning in the United States (Rutherford & Ahlgren, 1990). Despite these goals, a 2006 assessment found that students in all developmental stages lack science comprehension and reasoning skills (Grigg, Lauko, & Brockway, 2006). In a nation where the need for STEM professionals is increasing (Hurtado et al., 2012), the percentage of students completing corresponding degrees is decreasing. To investigate the reasons for this attrition, Seymour and Hewitt (1997) conducted a large-scale longitudinal study of college students in STEM degrees. They found two main reasons for attrition: disappointment with the curriculum and a loss of academic self-confidence in the highly competitive environment. Performance in introductory courses is directly correlated with students' retention in STEM degrees (Suresh, 2006). Therefore, the lack of these critical reasoning skills may be a causal factor in student attrition from STEM majors. Our objective in this study was to discover the common false strategies used by undergraduate students that lead to critical failures in using scientific reasoning.

These science process and reasoning skills (SPARS) are necessary for the 'scientific literacy' described by the American Association for the Advancement of Science (AAAS, 1993; Colvill & Pattie, 2002). Science Process Skills first became popularized in 1967 when a group of working scientists, commissioned by the American Association for the Advancement of Science (AAAS) observed scientists at

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work and defined the skills they were using (AAAS, 1967). These skills were categorized as 'basic' skills and 'integrated' skills. Basic skills included observing, using space/time relationships, using numbers, inferring, measuring, communicating, classifying, and predicting and are closely associated with what Piaget defined as concrete operational skills (Beaumont-Walters & Soyibo, 2001; Inhelder & Piaget, 1958; Zimmerman, 2000). Integrated skills included controlling variables, defining operationally, formulating hypotheses, interpreting data, and experimenting, skills closely related to Piaget's formal operational skills (Inhelder & Piaget, 1958; Zimmerman, 2000; Huppert, Lomask, & Lazarowitz, 2002; a correlation of 0.73 was found by Padilla, Okey, & Dillashaw, 1983). These skills are key factors to 'scientific literacy' described by AAAS (1993); Colvill & Pattie, 2002).

These skills have gone by many names over the decades including scientific process skills (OECD, 1999), procedural skills (e.g., Gott & Duggan, 1994), experimental and investigative science (National Curriculum; DOE, 1995), habits of mind (AAAS, 1993), scientific inquiry abilities (National Academy of Sciences, 1994), or scientific reasoning skills (Lawson et al., 2000). Kuhn (2002) defined them as intentional knowledge-seeking behaviors and the coordination of theory and evidence; Zimmerman (2007, p.172) defined them as "the skills involved in inquiry, experimentation, evidence evaluation, and inference that are done in the service of conceptual change or scientific understanding". Others have defined them as 'critical thinking skills' or 'science process skills' encompassing the skills used by scientists, such as identifying causal questions, proposing hypotheses, predicting outcomes, modeling, using mathematical reasoning, interpreting graphs, etc. (Bransford et al., 2000; NSF, 2000).

A lack of these skills persists in all ages including up to 50% of college-age adults (Kuhn et al., 1992; Kuhn & Franklin, 2006; Lawson, 1992; Schauble & Glaser, 1990; see Zeineddin & Abd-El-Khalick, 2010, for a review). An emergence of these skills is not developmentally or temporally constrained (Zimmerman, 2007). However, the full development of these skills likely does not occur without some explicit instruction or practice (Kuhn & Franklin, 2006). This requires an understanding of the common mistakes students make in using these skills.

Researchers have studied the development of several specific SPARS. For example, Kuhn and Phelps (1982) found that one of the strategies that led to success on a controlling variables task was note-taking. Shaklee and colleagues found a variety of rules being used when approaching evidence covariation tasks (e.g., Shaklee & Mims, 1981; Shaklee & Paszek, 1985; Shaklee et al., 1988). Several researchers have also shown that prior knowledge plays an influential role in how students approach a controlling variables task or how they interpret evidence (Koslowski, 1996; Kuhn et al., 1988). Yet much about the development of SPARS remains unknown, especially in adult learners.

Taking a broad view, there has been research done on general pedagogical strategies that lead to better conceptual understanding and critical thinking skills (see Bransford et al., 2000, for a detailed review). To summarize, a recent meta-analysis showed that student-center approaches to instruction lead to increased performance and decreases in failure rates, with an effect size that would lead to a stop in clinical trials for a treatment effect (Freeman et al., 2014). It has also been shown that these strategies can lead to gains in scientific reasoning ability (e.g., Heiss et al. 1950; Howard and Miskowski 2005; Jensen & Lawson, 2011; Minner et al., 2009; Renner et al., 1973; Rissing and Cogan 2009; Spiro and Knisely 2008). These types of findings are the basis for efforts outlined in publications such as *Vision & Change* in biology education (AAAS, 2011), *Reaching Students: What Research Says About Effective Instruction in Undergraduate Science and Engineering* (National Research Council, 2015) in all STEM fields, and *Scientific Teaching* (Handelsman et al., 2007). Thus, beyond explicit instruction of these skills themselves, implicit instruction can take place using a constructivist, student-center approach to science that focuses on higher-order cognitive skills (HOCS; Zoller, 1993).

Because the development of SPARS generally occurs during adolescence, the focus of most research, however, exists only in the K-12 literature. Nonetheless, many college students' scientific reasoning abilities are not proficient enough for them to excel in STEM classes. Very little research has been done to characterize scientific reasoning in adults and understand the barriers that keep adults from effectively using these skills. We hypothesize that common false strategies can be identified amongst college students that lead to difficulty in using these skills appropriately and transferring them within STEM subjects. In this study, we have defined the specific SPARS commonly used in STEM subjects and characterized common false strategies that college students use when attempting to implement STEM-related SPARS. By doing so, we have defined targeted areas for instruction that may lead to better performance, greater academic self-confidence, and increased retention in STEM degrees.

2. Research design

2.1. Defining SPARS

To test our hypothesis it was necessary to explicitly define SPARS. These skills first became popularized in 1967 when a group of working scientists, commissioned by AAAS (1967), were asked to define them. The skills were categorized as either 'basic', included observing, using space/time relationships, inferring, measuring, communicating, classifying, and predicting – all closely associated with what Piaget defined as concrete operational skills (Beaumont-Walters & Soyibo, 2001; Inhelder & Piaget, 1958; Zimmerman, 2000) – or 'integrated', included controlling variables, defining operationally, formulating hypotheses, interpreting data, and experimenting which are closely related to Piaget's formal operational skills (Inhelder & Piaget, 1958; Zimmerman, 2000; Huppert, Lomask, & Lazarowitz, 2002; Padilla, Okey, & Dillashaw, 1983). These skills are key factors to 'scientific literacy' described by AAAS (1993); Colvill and Pattie, (2002), and have gone by many names over the decades including scientific process skills (OECD, 1999), procedural skills (e.g., Gott & Duggan, 1994), experimental and investigative science skills (; DOE, 1995), habits of mind (AAAS, 1993), scientific inquiry abilities (National Academy of Sciences, 1994), and scientific reasoning skills (Lawson et al., 2000). Kuhn (2002) defined them as intentional knowledge-seeking behaviors and the coordination of theory and evidence; Zimmerman (2007, p.172) defined them as "the skills involved in inquiry, experimentation, evidence evaluation, and inference that are done in the