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Empirical study

Scaffolding scientific thinking: Students' evaluations and judgments during Earth science knowledge construction

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A B S T R A C T

Critical evaluation underpins the practices of science. In a three-year classroom-based research project, we developed and tested instructional scaffolds for Earth science content in which students evaluate lines of evidence with respect to alternative explanations of scientific phenomena (climate change, fracking and earthquakes, wetlands and land use, and formation of Earth's Moon). The present paper documents a quasi-experimental study where high school Earth science students completed these instructional scaffolds, including an explanation task scored for evaluative levels (erroneous, descriptive, relational, and critical), along with measures of plausibility reappraisal and knowledge. Repeated measures analyses of variance reveal significant increases in plausibility and knowledge scores for students completing instructional scaffolds that promoted students' evaluations about the connections between lines of evidence and two alternative explanations, whereas evaluations about connections between lines of evidence and only one alternative show no change in scores. A structural equation model suggests that students' evaluation may influence post instructional plausibility and knowledge. The results of this study demonstrate that students' active evaluation of scientific alternatives and explicit reappraisal of plausibility judgments can support deeper learning of Earth science content.

1. Introduction

Scientific literacy involves both knowing *what* scientists know and knowing *how* scientists know what they know. Recent science education reform efforts capture these two essential components (i.e., the *what* and the *how* of scientific knowledge) in a three-dimensional learning framework that intertwines scientific practices, crosscutting concepts, and disciplinary core ideas (National Research Council [NRC], 2012; NGSS Lead States, 2013). In this framework, evaluative processes act as a central hub linking the scientific activities of empirical inquiry and constructing explanations. Although the framework embeds reasoning throughout, evaluation as argument, critique, and analysis is central to scientific thinking and knowledge construction (NRC, 2012).

Evaluation often follows a dynamic and iterative cycle in the scientific enterprise. For example, some climatologists construct explanatory and predictive models representing Earth's atmosphere, and then collect empirical data to calibrate these models. Evaluation of connections between lines of evidence (e.g., sea surface temperatures) and scientific explanations (e.g., the interdependence of oceans and atmosphere) could lead to subsequent model refinements and validation with additional empirical data. Conant (1951) describes this dynamic and evaluative process as the speculative enterprise of science, where scientific knowledge construction is complex and requires mature, evaluative thinking (Kuhn & Pearsall, 2000). But such thinking may be difficult for students to learn and for teachers to teach (see, for example, Erduran & Dagher, 2014; Klopfer, 1969). Because of this difficulty, instructional scaffolds may be required to help students learn how to critically evaluate connections between evidence and explanations (Greene, Hutchison, Costa, & Crompton, 2012; Li et al., 2016) and construct scientifically accurate knowledge (Duschl, 2008; Sandoval & Reiser, 2004).

Our recent classroom-based research project focused on developing and testing instructional scaffolds—called Model-Evidence Link (MEL) diagrams[1]—that facilitate students' evaluations and judgments during knowledge construction (Fig. 1). Our project concentrated on the Earth science domain, which includes many topics that are challenging for

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[1] A team of researchers at Rutgers University developed the original structure and mode of the MEL (see Chinn & Buckland, 2012, for an overview). Lombardi, Sinatra, and Nussbaum (2013) and Lombardi, Bickel, Bailey, and Burrell (2018) adapted and expanded upon this design to fit within their theoretical framework positing the dynamic relations between evaluation, plausibility, and knowledge. The MEL is an instructional scaffold that facilitates students' evaluations about the connections between multiple lines of evidence and alternative explanations about a phenomenon (e.g., causes of current climate change).

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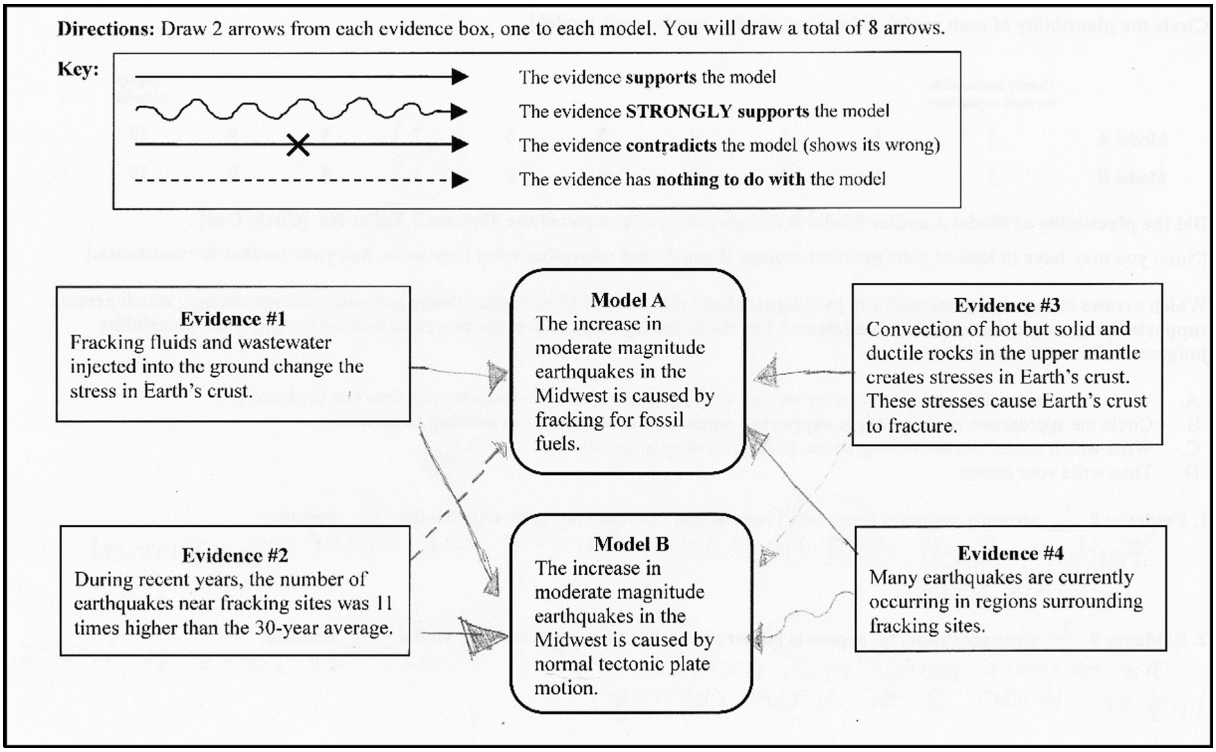

Fig. 1. A student example of the fracking Model-Evidence Link (MEL) diagram.

students because: (a) the underlying scientific principles are complex, (b) the processes frequently occur over very long time and large spatial scales, and (c) students have difficulty understanding how scientifically accurate explanations are constructed. Furthermore, some topics in Earth science are particularly salient because they concern issues of great local, regional, and global importance (e.g., climate change; see, for example, Sadler, Klosterman, & Topcu, 2011). Therefore, investigating scaffolds (e.g., the MEL) that help students think more scientifically about Earth science—specifically within a classroom context—may be both relevant and useful to systematically understand contemporary learning environments (Barab & Squire, 2004). Our project, and specifically the present study, comparatively examines MELs in authentic secondary classroom settings with the goal of gauging how Earth science students can deepen their knowledge about natural phenomena through scientific evaluations and judgments.

The present study examines the MEL in comparison to two other scaffolds. Lombardi, Nussbaum, and Sinatra (2016) argued that evaluative comparisons of alternative explanations could facilitate students' knowledge construction through increased cognitive engagement. Therefore, we specifically compared the MEL, where students evaluate connections between lines of evidence and two alternative explanations (i.e., the scientific alternative vs. another alternative), to the Mono-MEL, where students evaluate connections between lines of evidence and only one explanation (i.e., the scientific alternative). We also compared the MEL, where students evaluate connections diagrammatically, to the Model-Evidence Link Table (MET), where students evaluate connections using tables and letter codes. In subsequent sections, we elaborate further on our justifications for comparing these three scaffolds.

We built our project on a theoretical perspective that posits the following: learners may construct scientifically accurate knowledge through a process of generating explicit evaluations about scientific evidence and reappraising their plausibility judgments about explanations (Lombardi, Nussbaum et al., 2016). This perspective has both philosophical foundations (Rescher, 2009; Salmon, 1994), and empirical bases in educational, developmental, and cognitive psychology (Chinn & Brewer, 2001; Collins & Michalski, 1989; Connell & Keane, 2006; Dole & Sinatra, 1998; Kuhn & Pearsall, 2000; Nussbaum, 2011) and science education research (Braaten & Windschitl, 2011; Chi, 2005; Chinn & Brewer, 1993). Our discussion below highlights the extant literature supporting this theoretical perspective, as well as recent empirical work examining ways to promote scientific thinking and knowledge construction through more critical evaluations and judgments, and situates this perspective within the context of the present study.

1.1. Evaluation, plausibility, and knowledge

All scientific practices emerge from "processes of perpetual evaluation and critique that support progress in explaining nature" (Ford, 2015, p. 1043), and recent science education reform efforts call for students to engage in the scientific practices to help them achieve college- and career-readiness (NRC, 2012). To effectively participate in these practices, students should cognitively evaluate scientific evidence and "plausible explanation[s] for an observed phenomenon that can predict what will happen in a given situation" (NRC, 2012, p. 67). The scientific community also compares the plausibility of alternative explanations when constructing scientific models and theories. Yet within the context of certain Earth science phenomena (e.g., climate change and hydraulic fracturing, aka "fracking"), scientists may generate explanations that seem implausible to students. In contrast, alternative lay explanations about such phenomena – such as the notion that increasing amounts of energy received from the Sun are the cause of current climate change – may seem more plausible than scientific ones. Students may consider this lay explanation more plausible than the scientific explanation that human activities are the cause of current climate change. This difference in judgments about what explains a phenomenon is what Lombardi, Sinatra, and Nussbaum (2013) call a "plausibility gap."

Plausibility judgments may be associated with critical and scientific thinking. For example, Beyer (1995) says that questioning the plausibility of explanations is one characteristic of skepticism, a disposition of