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# The Role of Geoscience Education Research in the Consilience between Science of the Mind and Science of the Natural World

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## ABSTRACT

This manuscript addresses the potential role of geoscience education research in understanding geoscience expert practice. We note the similarity between the perception–action framework of Ulric Neisser (Neisser, 1976) and the observation–prediction framework used by geoscience practitioners. The consilience between these two approaches is that learning takes place when links are formed between predictions and observations and that this linkage is formed through conceptual models. Use of conceptual models facilitates learning at all levels; hence, there is little difference between learning in expert practice and student learning at all levels. The field of geoscience education is uniquely poised to enhance geoscience practice through investigation of expert learning, both in traditional field research and when experts adopt new tools and techniques. The consilience of expert practice, student learning, and cognitive science outcomes provides a rich opportunity to enhance both the intellectual merit of research and the direct and indirect broader impacts. © *2017 National Association of Geoscience Teachers*. [DOI: 10.5408/16-252.1]

*Key words:* cognitive science, understanding expertise, combining social and natural sciences

## INTRODUCTION

William Whewell is credited for coining the word *consilience,* composed of the Latin word for "together" (con-) and "jumping" (-siliens) (Whewell, 1840). His "consilience of inductions" was defined as when an induction (a derivation of a general principle from a specific observation, and a term also coined by Whewell) obtained from one class of facts coincided with an induction obtained from another class of facts (39). While Whewell used this term in the sciences, E.O. Wilson (1998) both popularized and expanded this usage to all human knowledge.

Regardless of whether you accept the details of Wilson's account of the mind or reject it (Pinker, 1998), we advocate considering the question: Can education research in the geosciences embrace consilience as a way forward? Geoscience education spans the affective domain and the learning domain (McConnell and van Der Hoeven Kraft, 2011). We argue that it also spans the domains of the mind and the natural world. Geoscience education can be supported by understanding how students learn (the realm of cognitive science and education research) in the context of understanding the natural world (the realm of the geosciences). As such, geoscience education research has created an intellectual domain between these two realms. Furthermore, it is the natural meeting ground for the consilience between these approaches, because no community knows the other communities' approaches sufficiently enough to use them fully. Galison (1997) argues that an interdisciplinary approach—one that brings two fields together—to work toward a common concrete goal has major advantages. For example, such an interdisciplinary approach can accelerate progress by removing barriers and foster progress in the absence of a Kuhnian (Kuhn, 1962) revolution.

In this commentary, we argue that consilience exists between cognitive science and geosciences and that this intersection has significant implications for geoscience education research. The perception–cognition cycle developed from cognitive science as an account of how humans understand ongoing events—articulated clearly by Neisser (1976)—has clear parallels to the observation–prediction cycle used by geoscientists. This parallelism emphasizes the role of the conceptual model in the observation–prediction cycle for both practicing geoscientists and traditional students. In this context—in which experts and students are learners—the traditional dichotomy between these groups disappears. Explicitly teaching conceptual models is one possible way in which to use the richness of this consilience.

## THE CYCLE OF OBSERVATION AND PREDICTION

The framework for discussion of the union of the social and natural sciences draws from a theoretical framework developed from Neisser's perceptual cycle. Neisser's (1976) approach was proposed as a way to think about how the mind developed an understanding of the world drawn from ongoing perceptual input. We recently explored this topic in detail (Shipley and Tikoff, 2016): Herein we summarize the results with an emphasis on the implications for geoscience education. But first, we must be explicit about the central issue: What is a conceptual model? A conceptual model is a mental model of the world that accounts for most observations and encapsulates current thinking in the field. More concretely, it is an interrelated set of representations of the world that allows inferences to be extracted that would answer "how" or "why" questions. For a geoscientist, it might include either a template or an exemplar of geometry,

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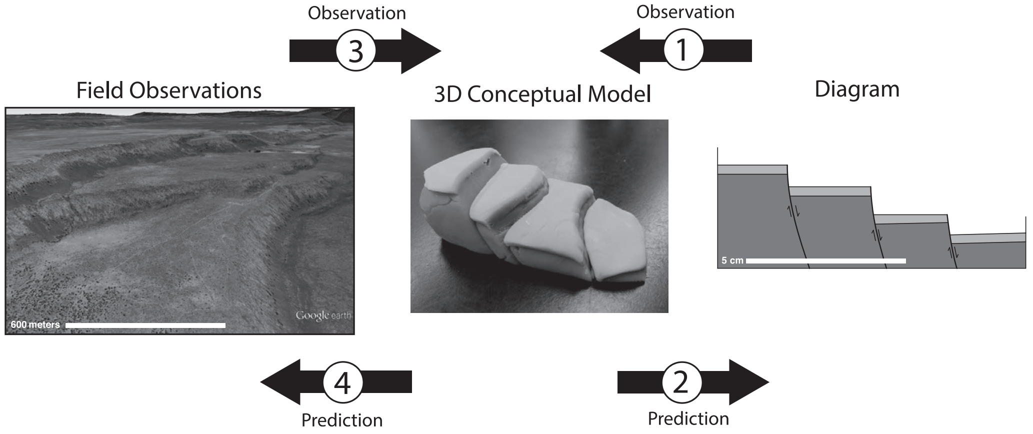

**FIGURE 1: An internal conceptual model (illustrated as a Play-Doh form in the central panel) is formed from observations of the world and from conceptual diagrams, which represent externalized conceptual models (arrows 1 and 3). The conceptual model may then guide further observations by making predictions (arrows 2 and 4). Conceptual models are retained as long as observations are consistent with predictions and revised when found to be inconsistent. (Shipley and Tikoff, 2016; AAPG, 2016; reprinted by permission of the AAPG, whose permission is required for further use.)**

kinematics, or some causal process (dynamic, thermodynamic, etc.). In the central part of Fig. 1, it is shown as a three-dimensional geometric model (represented as a solid model to illustrate the importance of accurate three-dimensional representations for useful geoscience conceptual models), but this is merely one type of conceptual model. Conceptual models, including geometric ones, are not necessarily solid or continuous; they need only be runnable (Gentner and Stevens, 1983) to make predictions. While research on mental models exists in the literature (e.g., Gentner and Stevens, 1983; Chi, 2000; Wiley and Meyers, 2003), relatively little is known about how experts use process-based mental models (MacLeod and Nersessian, 2016; Shipley and Tikoff, 2016).

Learning is a combination of observations that form the basis of an initial conceptual (mental) model of the world (arrow 1 in Fig. 1) and predictions made by the conceptual model of the world that guide further observations (arrow 2). Distinguishing between the external world and our internal conceptual model of the world is not new, and the alternative is naïve realism. However, two aspects of this framework are important. First, despite explicit recognition of the difference between the world and our models of the world (in such aphorisms as "all models are wrong; some models are useful"), the role of the mind in developing and refining a theory is generally segregated into other disciplines, such as philosophy of science. That is, the role of the mind in developing scientific concepts is not a conscious part of most expert practice. Second, the framework offers a basis for thinking about how mental (conceptual) models (and disciplinary theories) evolve over time.

The conceptual model is first developed from either observations about the world or an external representation of a model. This second route is illustrated by the cross section (diagram) on the right side of Fig. 1, which can be used to form an internal model. The internal model, however formed, must be runnable (Gentner and Stevens, 1983): It must allow the generation of new predictions about the natural world that can be tested by making new observations. The internal model is stable only as long as predictions match observations. If there is a mismatch, then the possibility for learning occurs: The internal model is either adjusted to accommodate the new observations or discarded for a model that better accounts for the observations. Changes of the internal model occur either incrementally, when new observations are incorporated into the model, or abruptly, when models are discarded for new models (Chi, 2008). Thus, an important point is that an internal model is subject to change.

Practitioners within the geosciences should find the above description familiar. There is a clear similarity to the normative practice of science, in which a cycle of prediction and observation are used to develop and support a theory (e.g., Riggs et al., 2009; Kastens et al., 2013; Bond, 2015). For example, this process is used continuously when conducting geological fieldwork (e.g., Gilbert, 1886; Hambrick et al., 2012; Baker et al., 2016). A field researcher arrives at a conceptual model by collecting data or by using the existing scientific literature. The geologist plans the approach (e.g., where to walk) and sampling based on this conceptual model. If unexpected data are encountered, the geologist may first try to slightly alter the conceptual model. If the unexpected data become sufficiently compelling, the old conceptual model is replaced by a new model that better explains the data (as advocated by, e.g., Freeman et al., 2010).

Critically, the above characterization of a malleable mental model should also be familiar to educators. In the ongoing cycle of learning in the geoscience classroom, there are opportunities and challenges for learning when making observations and making predictions. Our point here is that these opportunities and challenges exist for both students and experts.

We maintain that there is no substantive difference in kind between the learning that occurs as experts extend the boundaries of knowledge (e.g., MacLeod and Nersessian, 2016) and the learning that occurs as students extend the boundaries of their own knowledge (e.g., Chi, 2008). We do not intend to trivialize the practice of science. Learning to understand a new phenomenon is generally more difficult than learning about a phenomenon that is well understood with an agreed-upon characterization; concepts that took years of expert research to understand are routinely taught in a class period. While there are differences in the practice of learning by experts and students, the crucial point is that geoscience education research offers the opportunity to understand how to improve both student practice and expert practice.

## CONSILIENCE AND THE IMPORTANCE OF THE CONCEPTUAL MODEL

The opportunity we address here is the consilience of the conceptual (internal) model, as a meeting of inferences from different domains (cognitive science, geoscience education, and disciplinary geoscience research). Geoscience education has traditionally focused on the student's conceptual model. The scientific method is explicitly addressed, but classroom practice generally does not include work on disciplinary research problems—although with digital access to big data, this may change (Kastens et al., 2015). In contrast, disciplinary geoscience has focused on the expert's conceptual model (although not explicitly) and identifies individual learning as a special category: professional development. We are aware of no practices in the field or laboratory that frame disciplinary practice in terms of individual learning. Professional development is seen as an opportunity to develop new skills to be applied to practice; practice is not seen as a form of professional development. Practice and professional development appear to be treated as mutually exclusive. However, for both students and experts, the goal is to learn. Geoscience education research thus offers a common intellectual domain to develop a unified approach to learning. Just as all good teachers recognize that teaching can be improved to better support student learning (Kastens and Manduca, 2017), so too, we argue, can disciplinary research practice be improved to better support experts as they learn.

Although treated as a dichotomy, the differences between student learning and expert practice are not particularly significant relative to their similarities. In both cases, learning occurs when an internal (conceptual) model is inconsistent with either new data about the world or someone else's (e.g., an instructor's) explanation through diagrams or other means. A student's internal model could be different from what the instructor presented to the class. Almost all instructors have seen a student have a revelation (a lightbulb moment), when a new way of thinking about the data is presented. We suggest that this is the same process that happens to experts: Expert interpretation of the same set of observations could change radically with the development of a new schema. For example, consider the work of Atwater (1970), which connected ocean floor observations to land-based observations to explain the tectonic development of California. This is a case of someone (Tanya Atwater) sharing an internal model that changed how other colleagues thought about a problem.

Learning, or improving a model, can be supported; education research has developed ways to support students as they learn (Bransford et al., 1999). In addition to traditional pedagogy, a student bound for a career in the geosciences must learn to think like a geoscientist. Thus, it is important to understand how experts learn and teach students those habits of mind (Kastens et al., 2015). We need concrete answers to basic questions about conceptual models: What are the critical skills? Is there a hierarchy such that some models should be learned before others? What sort of guidance is best to support learning, and does that guidance depend on the level of expertise? How might effective geoscience student teaching strategies that support correcting mental models (e.g., spatial feedback; Gagnier et al., 2016) be adopted to support refining disciplinary mental models (e.g., in interdisciplinary groups; MacLeod and Nersessian, 2016)? Can we formulate any evidence-informed advice for instruction about conceptual models? Finally, are there individual differences in the skills necessary to develop and reason with conceptual models?

## AN EXAMPLE OF CHANGES IN PROFESSIONAL PRACTICE: STATISTICAL INFERENCE

Facilitating adoption of this broader view that encompasses K–12 students and disciplinary experts will likely require application of education research to challenges associated with a change in professional practice. We suspect that a point of access will be in new areas of professional practice in which the need to learn new skills is obvious to all. Of the major trends, we think that use of digital databases and robust statistical inference are two such areas in geoscience research generally and for field-based geoscience specifically. In both cases, experts are not necessarily trained in these tools; hence, their learning is similar to student learning. Because there are clear cases in which disciplinary practice is changing, these topics provide valuable opportunities to observe and support learning throughout the discipline. In this section, we try to illustrate how our framework might guide geoscience education in studying and supporting these transitions for the example of statistical inference.

Field-based geoscience, as a historical science, has made much progress on a foundation of trained observers who make a small set of high-quality observations. These observations are selected to be representative of a region and allow discrimination among competing hypotheses. Part of our analyses must include understanding the natural variability in data, and as our awareness grows of the potential for observers to be biased in their selection of observations, more observations are being made about a single location. With the advent of multiple observations comes the need for statistics to characterize the collection of observations and assist in discriminating among data sets that represent differing populations.

Consideration of variability was not absent in the classical practice of field data collection, but it was likely unconscious. Field data collection practice, as simple as selecting a bedding plane at an outcrop to measure strike and dip, requires mental selection. Factors that enter into the selection include the practical (e.g., which location minimizes time, energy, and risk) and the statistical (e.g., which location is consistent with or representative of all of the potential locations visible to the observer). The latter selection, which may require explicit guidance when first learned, becomes second nature for the expert. Selecting a representative location requires visually estimating the values at many locations and selecting the location that is the central tendency of the set. Unconsciously, the observer's visual system has performed a statistical operation akin to calculating the mean. Higher-order statistical properties are likely also assessed. If, for example, the distribution of visual estimates appears unimodal, a single observation would be sufficient; if multimodal, the observations of the best estimator of each mode are required.

From the perspective of conceptual models, one might ask, what counts as disconfirmation of a conceptual model? Obvious cases are categorical errors (e.g., a trend should increase but it goes down), while less obvious cases occur when an observation is outside of an expected range. Here, geoscience education may employ what we know about how students can learn despite variability (e.g., Nosofsky, 2015) to support experts as they learn to explicitly test predictions that were once likely done implicitly (often by a well-trained visual system).

In this endeavor, the sciences of the mind have long recognized that there is substantial variability between and within minds. This discipline offers sophisticated tools for characterizing variability and for making inferences about underlying processes based on patterns of variability. Thus, it can offer guidance on the value of variability to learning. There is scientifically important information about variation in the natural world that has heretofore been resident only in the visual systems of experts. The advent of statistical analyses that allow characterization and hypothesis testing of complex spatial data (e.g., Davis and Titus, 2017) offers experts new tools for developing and evaluating models that include higher-order spatial properties. Adoption of statistical methods may be facilitated by geoscience education research revealing the expertise in implicit spatial statistics that is the product of traditional field training and by supporting explicit understanding of the scientific value of statistics. This specific convergence of social and natural science tools and problems again highlights the potential role of the geoscience education researcher who spans the two communities and can help construct a bridge between them.

## GEOSCIENCE EDUCATION RESEARCH: THOUGHTS FOR FUTURE WORK

How does this framework guide education in both formal and informal settings for students and professional development? We argue that attention to the conceptual model is key. In disciplinary science, we expect a theory to make predictions (although they have other functions, such as organizing observations). To make a prediction, a theory must have a predictive (or runnable) model (Gentner and Stevens, 1983). The same is true for student learning: Students need to have a runnable model. The Next Generation Science Standards (NGSS Lead States, 2013) include a discussion of the importance of models, and some curricula include attention to models. Our framework highlights the need to offer students conceptual models in a form that, if fully understood, makes predictions. Students also need explicit experience refining models with new data and testing (and rejecting) models when observations do not fit them (Gilbert and Justi, 2016). Again, these are critical skills necessary to disciplinary expertise that may not be explicitly taught until the graduate school level (Bond et al., 2011).

Our framework emphasizes the importance of the experts' library of conceptual models, which they can check against observations (Gentner and Stevens, 1983). In the case of some geological feature that is not in their suite of conceptual models, experts will either search the relevant literature for a model or, in rare instances, come up with a new conceptual model. If this is how researchers operate, and if the goal of a student is to develop expertise, it is straightforward that there should be a focus on developing the student's array of conceptual models and practicing refining and replacing models. Several types of geoscience educational design patterns might support this skill (Kastens et al., 2015; Alcalde et al., 2017).

There may be two kinds of barriers to adoption of this approach by the geoscience community. The first barrier is related to the traditional academic division between social and natural sciences. Experts are generally not aware of their own cognitive processes (e.g., Bransford et al., 1999). Consequently, it is difficult to directly teach how they solve disciplinary problems. Because knowledge of the mind is not part of a natural scientist's practice, learning (teaching) and research are compartmentalized concepts, and practices in one do not influence the other. Yet, the geoscience education research community has made significant progress on a similar type of barrier at the level of college instruction through professional development (Manduca et al., 2017). Recognizing the first barrier would expand the domain of geoscience education, put the geoscience education on equal intellectual footing with all other geoscience subdisciplines (as the science of how to do the science), and offer a way to collect data relevant to supporting learning throughout the development of expertise.

The second kind of barrier is that the best way to develop a student's repertoire of conceptual models is not well understood (e.g., Muller, 2014; Alcalde et al., 2017). Lowering the second barrier is an agreed-upon goal of geoscience education research.

In advocating for recognition of the role of the mind in the practice of geoscience, we are not taking a postmodern approach to science in which social beliefs influence the nature of the geosciences. Surely, the natural world does not care what our theories are—in cognitive science, social science, or geoscience. However, in the social sciences, a theory can change the behavior for which it accounts. Schwartz (2015) refers to this as a "technology of ideas" (65). We are advocating for an idea that could change how geoscience is practiced because it changes the way geoscientists think about the role of their minds in both practicing and teaching their science.

## INTELLECTUAL MERIT AND BROADER IMPACTS

How might this approach be useful to the teacher? This commentary is primarily aimed at the geoscience education researcher. Explicit consideration of the role of conceptual models in learning offers a new perspective on learning. Ongoing design-based research is considering potential advantages of explicitly acknowledging these models in a classroom and using this framework as a narrative for classroom experience. Whether such an approach is useful is an open question. The framework also offers instructors a way to think about the concepts they are teaching (e.g., runnable models) and how different design patterns might support learning.

How might this approach influence the geoscientist? We argue, simply, that training students is grounded in the conviction that the minds of students can be improved and thus they can become better scientists. We are also arguing that the minds of the experts can be improved; thus, they too can become better scientists. We readily admit that the devil is in the details, but the path to the research on those details requires an expansion of horizons.

Because this idea is relatively new, there are a lot of questions about its implementation—at both the student and the professional level. Research focuses on basic questions for the students: Should they be introduced to the concept of a conceptual model? When should they start using models for prediction? How should statistics and variability be introduced to students and experts? Alcalde et al. (2017) show that multiple examples of nonideal fault geometries are necessary for people to correctly interpret seismic sections. Thus, it appears that variability in example is as critical for expert practice as it is for student learning (Nosofsky, 2015). For experts, we know humans show systematic biases and errors in reasoning (e.g., Kahneman and Tversky, 1996). How should individual practice be structured to avoid or minimize the biases of individual minds?

Finally, many major scientific arguments have been over conceptual models (Oreskes, 1999). Being explicit about what the conceptual model is, which ones are being used, and what data do and do not support them may allow more useful conversations, quicker (and nonpersonal) resolution to scientific differences, and better science to test among different models.

## CONCLUSIONS

Our main argument is that there is a consilience of expert practice, student learning, and cognitive science. The consequence is that geoscience education, which has been mostly applied to student learning, might inform both professional training and practice through an investigation of expert learning. An example of this type of research program already exists for seismic interpretation training (e.g., Bond et al., 2007; Bond, 2015; Alcalde et al., 2017). The consilience is possible by the integration of cognitive science principles into geoscience practice and teaching. The sciences of the mind bring two powerful ideas to the sciences of the natural world: (1) that the role of the mind in the practice of science is discoverable and (2) that we can apply what we know about learning—the science of learning—to the science of the natural world. By expanding geoscience education's hegemony from the classroom to disciplinary practice, there is opportunity to improve all geosciences.

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