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Using an engagement lens to model active learning in the geosciences

N. D. LaDue[a], P. M. McNeal[b], K. Ryker[c], K. St. John[d], and K. J. van der Hoeven Kraft[e]

[a]Department of Geology & Environmental Geosciences, Northern Illinois University, DeKalb, Illinois; [b]Department of Physics, Astronomy & Geosciences, Towson University, Towson, Maryland; [c]School of the Earth, Ocean & Environment, University of South Carolina, Columbia, South Carolina; [d]Department of Geology & Environmental Science, James Madison University, Harrisonburg, Virginia; [e]Sciences Department, Whatcom Community College, Bellingham, Washington

ABSTRACT

Active learning research emerged from the undergraduate STEM education communities of practice, some of whom identify as discipline-based education researchers (DBER). Consequently, current frameworks of active learning are largely inductive and based on emergent patterns observed in undergraduate teaching and learning. Alternatively, classic learning theories historically originate from the educational psychology community, which often takes a theory-driven, or deductive research approach. The broader transdisciplinary education research community is now struggling to reconcile the two. That is, how is a theory of active learning distinct from other theories of knowledge construction? We discuss the underpinnings of active learning in the geosciences, drawing upon extant literature from the educational psychology community on engagement. Based on Sinatra et al. engagement framework, we propose a model for active learning in the geosciences with four dimensions: behavioral, emotional, cognitive, and agentic. We then connect existing literature from the geoscience education community to the model to demonstrate the current gaps in our literature base and opportunities to move the active learning geoscience education research (GER) forward. We propose the following recommendations for future investigation of active learning in the geosciences: (1) connect future GER to our model of active learning in the geosciences, (2) measure more than content learning, (3) document research methods and outcomes with effect sizes to accumulate evidence, and (4) prioritize research on dimensions of active learning essential to the geosciences.

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Active learning; geoscience education research; engagement; discipline-based education research

Introduction

Geoscience Education Research (GER) is a nascent community of practice (Arthurs, 2019; Lukes et al., 2015) relative to other discipline-based education research (DBER) fields (National Research Council, 2012). Nevertheless, the community is highly engaged in active learning in the classroom (Egger, 2019, Mosher & Keane, 2021). Approximately 20% of all U.S. geoscience faculty have participated in the National Science Foundation (NSF)-funded Cutting Edge program (Manduca et al., 2017), which over the course of two decades, emphasized student-centered active learning and influenced the norms for geoscience teaching practice (Viskupic et al., 2019). Analysis of teaching practices survey data from one quarter of the ~10,000 faculty teaching geoscience in the U.S. demonstrate that the preceding decade of investment in faculty professional development led to increases in faculty implementation of active learning strategies (Manduca et al., 2017). Their data showed that between 2004 and 2012, faculty respondents reporting the use of active learning strategies in their classes increased from 42% to 57%. The extant research on active learning in the GER literature is dominated by articles emerging from practitioner wisdom (e.g. Johnson & Reynolds, 2005) and cohort studies (repeated research studies across classes, instructors, and/or institutions; e.g. McConnell et al., 2006), with a few case studies (single iteration of a research study; e.g. McConnell et al., 2017; Quinn et al., 2003). Aside from the cohort studies, these study designs are classified as relatively low on the Strength of Evidence Pyramid presented in St. John and McNeal (2017); however, they reflect the roots of GER — a strong community of reflective educators who care deeply about teaching practice and student learning.

Active learning is not well defined in the literature (Lombardi et al., in press; Driessen et al., 2020), due largely from the disparate disciplines from which the concept emerges (Idsardi, 2020). Mintzes (2020) reports on the emergence of the term *active learning* from teaching practice in higher education in the late 1980s but echoing psychology and education theory from much earlier. The term *active learning* emerges in the GER literature around the year 2000 (McConnell et al., 2003; Murck, 1999; Yuretich et al., 2001). McConnell et al. (2003) initially framed active learning as engaging students in applying what they are learning within the class and nearly two decades later, the GER community has accumulated considerable evidence in support of several

CONTACT Nicole D. LaDue nladue@niu.edu Department of Geology and Environmental Geosciences, Northern Illinois University, 1425 West Lincoln Hwy, DeKalb, IL 60115, USA

active learning strategies. More recent GER publications provide two contrasting approaches to defining active learning. McConnell et al. (2017) defined active learning as students engaged in two or more of the following in addition to, or instead of, listening to direct instruction: (1) doing or observing, (2) reflecting or formative assessment, and (3) peer-to-peer interaction (McConnell et al., 2017). This definition is intentionally broad to encompass many pedagogical strategies. A second framing of active learning by Arthurs and Kreager (2017) adopted the definition of active learning used in Freeman et al. (2014), and framed active learning within the theoretical context of constructivism (Vygotsky, 1934; 1986) and social interdependence theory (Lewin, 1935). Within this context, Arthurs and Kreager (2017) categorized types of active learning based on how much peer interaction and positive social interdependence occur.

McConnell et al. (2017) definition of active learning acknowledges both individual engagement behaviors (e.g., doing or observing, reflecting) and instructional practice (e.g., formative assessment, peer-to-peer interaction). Arthurs and Kreager (2017) reference theories about "how learners come to know" (Airasian & Walsh, 1997, p.445) through active knowledge construction (e.g., constructivism) and social interaction. These examples demonstrate a tension between the individual context of knowledge construction, which constructivists would argue is always active (Bruner, 1966, 1973, 1985), and the learning context of an instructional setting, where strategies are employed to facilitate individual knowledge construction (Airasian & Walsh, 1997). We acknowledge that learners themselves can engage strategies that facilitate their learning (e.g., metacognition, note taking) without an instructional strategy that structures their engagement. Cerbin (2018) reviews literature from psychology and education research on learning and connects it to instructional strategies that an instructor may employ to promote learning in lecture. Many of Cerbin's examples are activities that efficient learners already do without instructor guidance (e.g., activate prior knowledge, look for patterns, reduce distraction, review and consolidate learning).

A recent review of the biological sciences education research literature established a consensus definition of active learning that includes both student engagement and the employment of strategies (Driessen et al., 2020). The term active learning emerged from a higher education context (Mintzes, 2020), and therefore a definition that includes instructional practice is logical and useful. However, the instructor-driven perspective alone, without the context of a rich literature base from education and psychology research on the type of student knowledge construction that epitomizes active learning, hinders the community from effectively accumulating evidence. Therefore, we propose engagement as a theoretical lens for examining active learning. This lens affords a broader view on active learning than currently exists in GER and can be used to develop a model of what constitutes the *active* component of learning in the geosciences. In reviewing GER evidence for this model, we subsume the distinct categories of active learning strategies that may be employed by either the student or the instructor *and* active learning instructional strategies that are employed by the instructor to engage students. The purpose for this is two-fold: 1. The nascent nature of the GER community means there are fewer studies from which to draw examples, and 2. The mechanism for learning we adopt (i.e. engagement) may be enacted by individuals independently or structured by the instructor through instructional strategies.

Study context and purpose

This project began as part of a collaborative effort to develop a theory of active learning in STEM (Lombardi et al., in press) with a network of transdisciplinary education researchers (DBERs, educational psychologists, cognitive psychologists). There is more literature on the adoption of active learning strategies by faculty (Grunspan et al., 2018), the implementation of active learning in the classroom (Stains et al., 2018), and the definition of active learning (Driessen et al., 2020; Idsardi, 2020) than on the theoretical underpinnings of active learning (Arthurs & Kreager, 2017; Lombardi et al., in press), due in part to this genesis from disparate disciplines (Idsardi, 2020). This Commentary emerged from the authors' participation as the Geoscience Team for a transdisciplinary effort to define a theory of active learning (Lombardi et al., in press). Our disciplinary scope included education research in geology, marine science, and meteorology/atmospheric science, but not planetary geology or geography, explicitly. These boundaries were pre-determined through discussion with the collaborative team and do not imply any judgment on the relative value of a particular discipline's literature.

Our purpose in this Commentary is to: (1) introduce a model for framing active learning research in the geosciences through the lens of engagement; (2) connect existing geoscience education research to the newly introduced model; and (3) present recommendations for using the model to strengthen evidence and active learning research in the geosciences. To accomplish this, we drew literature primarily from the *Journal of Geoscience Education* (JGE) because the scope of JGE is most closely aligned with our purpose. We did not attempt to conduct a complete literature review and therefore acknowledge that there are likely additional valuable studies that could have been included.

Active learning through an engagement lens

In a 2004 review of research on learning, Fredricks et al. describe three dimensions of school engagement: *behavioral, emotional* and *cognitive. Behavioral* engagement can be evidenced through student actions, including attendance and participation (Fredricks et al., 2004). *Emotional* engagement occurs when students feel a sense of belonging, interest, and value (Fredricks et al., 2004). *Cognitive* engagement is defined as self-regulation, motivation, and challenge-seeking behaviors that lead to deeper learning (Fredricks et al., 2004). A concern Fredricks et al. (2004) raise is the use of the term *effort* in the context of cognitive engagement

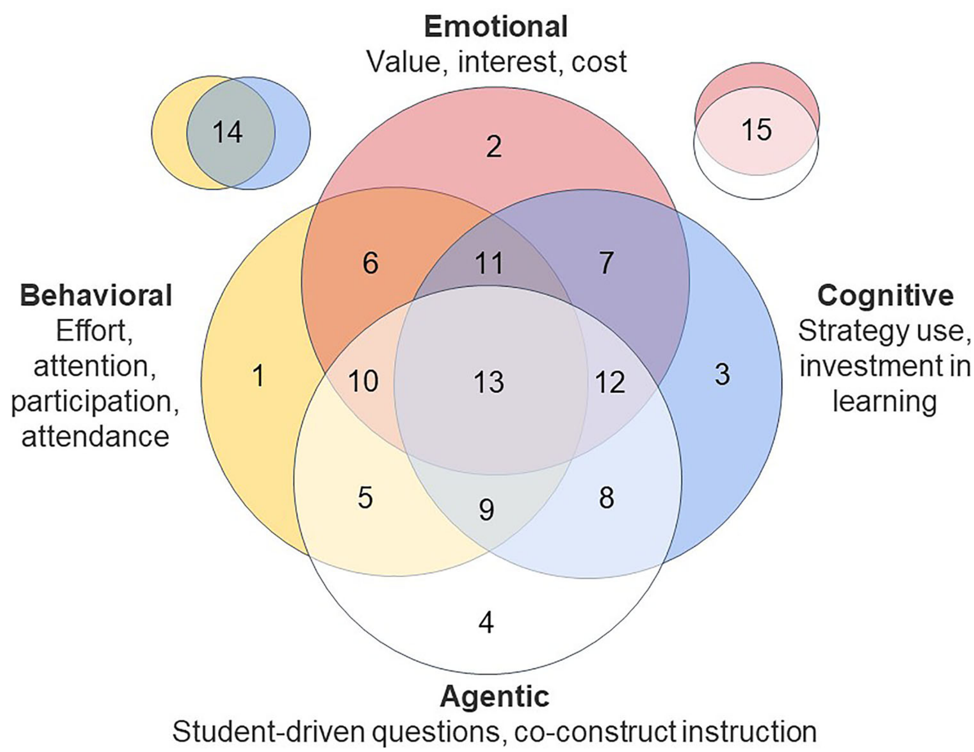

Figure 1. Our model of active learning in the geosciences based on the four dimensions of engagement (Sinatra et al., 2015). Numbers mark different regions in the mode. Some regions (i.e., #1-4) are pure end members of engagement dimensions. All other numbered regions are overlaps with two or more engagement dimensions. Active learning interventions and research are positioned within this multi-dimensional landscape of engagement.

because it overlaps with aspects of behavioral engagement. For example, a student can put in the time studying (e.g., behavioral engagement), but that doesn't mean that they engaged in strategies that deepen learning (e.g., cognitive engagement). Fredricks et al. (2004) and Sinatra et al. (2015) also caution that motivation and self-regulation are woven throughout the dimensions of engagement so are not limited to the category of cognitive engagement. In an attempt to apply the concept of engagement to science learning, Sinatra et al. (2015) incorporated a fourth dimension, *agentic* engagement, from Reeve & Tseng, 2011 (Figure 1). *Agentic* engagement occurs when "a student actively contributes to the flow of instruction" (Sinatra et al., 2015, p. 3). Sinatra et al. (2015) acknowledge that the component view suggested by a model containing four dimensions is problematic because many learning theories, such as Social Cognitive Theory (Bandura, 1986), Situated Learning Theory (Lave & Wenger, 1991), and Expectancy-Value Theory (Eccles,1983; Pintrich & De Groot, 1990), involve multiple dimensions of engagement within a single learning episode or context. Therefore, we present a visual model that represents these spaces as overlapping (Figure 1) and discuss GER findings within the context of this multi-dimensional space. It is important to note that there are other models of engagement in the literature (Chi & Wylie, 2014). Chi and Wylie (2014) ICAP framework describes four engagement behaviors and is particularly valuable for evaluating active learning during a classroom observation. However, we felt the ICAP framework is not sufficiently broad in scope to incorporate geoscience-specific learning contexts, such as field and laboratory learning and therefore we focus on the four dimensions described by Sinatra et al. (2015) to elaborate a model of active learning in the geosciences. Additionally, Sinatra et al. (2015) acknowledge that most learning occurs within the context of multiple dimensions of engagement so these dimensions are not exclusive of one another. We choose to align GER findings to these dimensions, and when appropriate the overlapping spaces, to bring clarity to the gaps within the GER literature and facilitate decision-making for researchers in selecting appropriate theoretical lenses for their active learning research.

An illustrative case of engagement in geoscience

To illustrate how a student might experience multiple dimensions of engagement in a geoscience context, consider an introductory student at a community college, Jessica. Jessica is told she needs to take a science class in order to graduate, so she enrolls in an introductory geology course because she thinks it sounds the most interesting and perceives it as less difficult than other sciences courses (Lewis, 2008; Wilson, 2018), but doesn't have a lot of self-efficacy in doing science (Gilbert et al., 2012). Jessica's instructor is particularly engaging, so her motivation increases in class and she engages more emotionally and employs skill sets she has learned from other classes to successfully do the course work (Pintrich & De Groot, 1990), which means she is both emotionally and cognitively engaged. She may even ask questions, based on her life experiences, that influence some aspects of what the instructor brings into the classroom, indicating agentic engagement. However, Jessica struggles with the fact that every other person in the class is white, her instructor is white and all the photos of geologists are white (Sexton et al., 2014). As a Latina woman, she does not see herself represented, which can result in a negative emotional response and lower her motivation. These interactions between multiple dimensions of engagement illustrate the underlying complexity of active learning. Because the Sinatra et al. (2015) framework can be applied to classroom, lab, and field contexts and because it effectively targets multiple dimension that contribute to knowledge construction, we use the Sinatra et al. (2015) framework to support a model of active learning in the geosciences.

A model of active learning in the geosciences

We propose a model of active learning that can guide the framing of GER active learning research, enabling the community to accumulate knowledge and evidence from reviews of existing literature and identify gaps to pursue for future research (Figure 1). The four dimensions, *behavioral, emotional, cognitive,* and *agentic*, are aligned with the dimensions as defined by Sinatra et al., 2015. GER studies that measure one or more of these dimensions already exist in the literature. For example, d'Alessio et al. (2019) used course page visits as a metric for *behavioral* engagement. Cohn et al. (2014) and Gilbert et al. (2012) assess connection to place and task value as measures of *emotional* engagement. In science education, *agentic* engagement is similar to robust inquiry learning where students develop the question, design an experiment, and interpret the results (Grissom et al., 2015; Ryker & McConnell, 2017). Course grades (i.e., achievement) and performance on learning inventories (e.g. the Geoscience Concept Inventory; Libarkin & Anderson, 2005) may be indicators of cognitive engagement but should not be used as a direct measure of cognitive engagement. For example, a student may be cognitively engaged but fail to build new knowledge if the cognitive load of the task is too high (Mayer, 2004; Sweller et al., 2007). Research on cognitive engagement should investigate the process accounting for gains in achievement.

Although most active learning contexts involve multiple dimensions simultaneously whether they are measured or not, research on active learning often measures only one or two dimensions at play. Next, we describe examples from the extant GER literature that investigate various aspects of student engagement. We organize these based on the four dimensions presented in Sinatra et al. (2015) to provide a richer understanding of the dimensions and some of the evidence the GER community has accumulated thus far. A study's dominant dimension determines within which section it is included in the discussion that follows. Studies that describe intersections between multiple dimensions of engagement, or assert a particular dimension without sufficient measurement, were grouped in the dimension of engagement that was described by the authors in the original published paper. As a consequence of the uneven accumulation of published evidence in GER for each engagement dimension we have grouped studies that are theory-building with pedagogical interventions where a predictor or independent variable relates to a particular engagement dimension. Where available, we report effect sizes using the convention used by the author. For Cohen's d, effect sizes of 0.20-0.49 are small, 0.50-0.79 are moderate, 0.80-1.29 are large, and above 1.30 are very large (Cohen, 1992). For Cramer's V (φ), effect sizes of 0.10 are small, 0.30 are medium, and >0.50 are large (Cohen, 1988). For partial eta squared (η^2), effect sizes of 0.0099 are small, 0.0588 are medium, and over 0.1379 are large (Richardson, 2011).

Connecting existing geoscience education research to the dimensions represented in the model

Behavioral engagement in the geosciences

Student behavior is evident in the classroom, therefore one way to measure behavioral engagement is through classroom observations. Focusing directly on student behavior (Region 1 of Figure 1), Lane and Harris (2015) developed and validated a classroom observation protocol for quantitatively measuring student behavioral engagement, which they defined simply as on-task behavior. The Behavioral Engagement Related to Instruction (BERI) protocol was developed after noticing differences in student behavioral patterns in the classroom that related to different instructional methods. Lane and Harris (2015) documented substantially higher engagement when interactive teaching methods were used compared with more traditional didactic methods; in particular, the most engaging activities were clicker questions and clicker question follow-up. Lane and Harris (2015) note that whereas the BERI may measure whether or not a student is engaged, it cannot confirm how deeply the student is cognitively processing the material to be learned. To exemplify, students who engage in rote note taking may not be cognitively engaged while students who, during lecture, use sketching to increase their understanding could be coded as inattentive. Although this exposes the limitations of this and other protocols, it highlights the importance of eliciting multiple engagement dimensions simultaneously. Recognizing this, there are several, well-developed, research-validated observation protocols that could strengthen the claims researchers make about the fidelity of active learning, especially as it relates to behavioral engagement.

Multiple GER studies that primarily investigated teaching practices also used observation protocols that included student behavior as a measure. Both Teasdale et al. (2017) and Viskupic et al. (2019) described the use of the Reformed Teaching Observation Protocol, or RTOP (Budd et al., 2013), that included observations of student behaviors such as the amount of time students were quietly listening, versus working by themselves or with peers. Although Teasdale et al. (2017) focused on reformed teaching practice, they concluded that instruction in student-centered classrooms resulted not only in engaging students in class activities with one another, but provided opportunities for students to answer and pose questions that determined the focus of the lesson (an overlap of behavioral and agentic dimensions, represented by Region 5 in Figure 1).

An increasingly common way to encourage behavioral engagement during lecture-based instruction is by asking students to respond to concept tests (McConnell et al., 2006) or other short questions, with or without a classroom response system (CRS), such as clickers, Poll Everywhere, or Top Hat (LaDue & Shipley, 2018; Resnick et al., 2017b). This method of behavioral engagement can be enhanced when combined with activities that encourage engagement of the remaining dimensions. For example, McConnell et al. (2006) combined higher-order multiple choice questions asked after lecture with peer instruction (students were directed to discuss the reasons for their answer choice with a neighbor for 1-2 minutes). The complexity of concept test questions, in contrast to simple recall questions, likely increased cognitive engagement. McConnell et al. (2006) found that, based on student and instructor feedback, concept tests increased attendance, improved student satisfaction, and enhanced student achievement. This study provides an example of successful behavioral engagement that simultaneously increased emotional and likely increased cognitive engagement, and therefore we placed it in Region 11 of Figure 1. However, because the McConnell et al. (2006) study measured cognitive engagement through learning gains it is only suggestive of cognitive engagement. Written or verbal data revealing student reasoning while completing the concept test questions would provide stronger evidence of cognitive engagement. LaDue and Shipley (2018) expanded on this idea by using click-on-diagram questions administered using Top Hat to identify and provide efficient access to students' spatial understanding of different geoscience topics. In their study, LaDue and Shipley (2018) combined methods for eliciting student behavioral engagement with a tool for investigating students' spatial misconceptions that can inform subsequent instruction and promote conceptual change, represented by Region 14 of Figure 1. They also demonstrated a large effect ($\varphi = .82$) of instruction on students' changing conceptions about Earth's interior structure. Many previously investigated GER instructional strategies, such as practicing observation-prediction cycles (Kreager & LaDue, 2018; LaDue & Shipley, 2018; Shipley & Tikoff, 2017), using gestures (Atit et al., 2015; Ormand et al., 2017; Van Boening & Riggs, 2020) and using sketching (Johnson & Reynolds, 2005; Ormand et al., 2017; Reusser et al., 2012) could additionally be investigated for their ability to increase behavioral engagement.

Another example of increasing behavioral engagement is the use of two-stage exams (Bruno et al., 2017; Eaton, 2009; Knierim et al., 2015; Yuretich et al., 2001), which involve students in structured collaborative exams in addition to an individual exam component. Two-stage exams leverage social interdependence, which can be a powerful motivation for students to behaviorally engage with peers and assessment material (Arthurs & Kreager, 2017). Bruno et al. (2017) reported a large effect size of 1.3 (Cohen's *d*) for achievement gains in both high- and low-performing students when comparing performance on individual and group stages of exams administered in undergraduate oceanography and geology classes (Region 14 of Figure 1). Similarly, Yuretich et al. (2001) reported increased attendance and interest in science in a large introductory oceanography course that included two-stage exams along with other cooperative learning exercises, indicating that an emotional component was at play as well (Region 11 of Figure 1). Two-stage exams are an intervention that structures behavioral engagement (i.e., working with peers), but cultivate elaboration and reflection of one's ideas (cognitive engagement) and positive social interdependence (emotional engagement). Measurement of additional variables associated with cognitive and emotional engagement would add to our understanding of the mechanism of two-stage exams as an effective active learning tool.

Finally, of increasing interest, especially spurred by adaption of teaching during the coronavirus pandemic, is the ability to effectively engage students during online learning. There is a growing body of instructional resources for online geoscience courses that are becoming ever more organized and accessible. Investigations of online graduate Earth science courses with K-12 teachers (Gosselin et al., 2010; Schwerin et al., 2006) tested strategies that focused on theory, teamwork, practice, feedback, reflective learning and metacognition. Asynchronous chat strands additionally lent some measure of agentic engagement (Schwerin et al., 2006; Region 13 of Figure 1). These studies are especially relevant as we seek to propel our understanding of active learning in online settings forward. d'Alessio et al. (2019) included measures of behavioral engagement in online geology courses to understand how social engagement in the course influenced learning. Using a Community of Inquiry framework, d'Alessio et al. demonstrated that social and cognitive presence were of dual importance in significantly predicting student performance. When students felt connected to one another and the instructor (social presence), they were more productively engaged in connecting ideas (cognitive presence). d'Alessio et al. (2019) measured behavioral engagement of the instructors and students using data from the learning management system (e.g., course announcements, median instructor response time to students' posts, and students' use of photos as avatars on discussion boards). The study is another example of one that occupies Region 11 of Figure 1, where behavioral, emotional and cognitive engagement overlap. Other studies have evaluated different aspects of online learning, such as discussion boards (Clary & Wandersee, 2014) and demonstrated that they have a moderate effect on geoscience understanding (Cohen's $d = 0.48$). More research is needed to understand aspects of engagement in online courses and how learning analytics associated with student behavior in an online environment can reveal student engagement (Siemens & Baker, 2012).

Emotional engagement in the geosciences

In the educational psychology literature, some authors (e.g., Blumenfeld et al., 2004) describe superficial examples of emotional engagement (e.g., demonstrations with explosions). We are not using the term in this manner. Emotional engagement is strongly linked to motivation, as it encompasses value, interest, and cost. van der Hoeven Kraft et al. (2011) proposed a geoscience-specific theoretical framework of emotional engagement (Region 2 of Figure 1) that included *place attachment*, *connections to esthetic, identity, and interest* as important dimensions to investigate. Place-based education emerged from programs that sought to connect learning and community (Smith, 2002: Sobel, 2004) and to engage students emotionally through their existing or emerging sense of place (Semken & Butler-Freeman, 2008; Semken et al., 2017). Several examples demonstrate the role that place attachment has in students' emotional engagement, and in turn, its potential impact on student learning in the geosciences. Hammersley et al. (2012) found that Hispanic students enrolled in a Geology of Mexico course (modeled on traditional Physical Geology but using Mexican case studies to illustrate concepts) created a true community of practice (Lave & Wenger, 1991) that used "a shared repertoire of communal resources developed by the members of the community" (p. 197). An unintended consequence of the place-based course design was creation of student cohorts that shared cultural and linguistic background as well as life experiences, which heightened their sense of belonging. Overall, this study is a clear example of one at the intersection of cognitive and emotional engagement (Region 7 of Figure 1). Hammersley et al. (2012) found that the average increase in score from pre- to post knowledge tests for the Geology of Mexico students was significantly greater than the increase in score for Physical Geology students; additionally, students in the Geology of Mexico course displayed more positive attitude changes and were more likely to take additional geology courses. Semken and Butler-Freeman (2008) applied the Place Attachment Instrument (Williams & Vaske, 2003) and the Place Meaning Survey (Young, 1999) as tools to assess a place-based introductory geology course and observed significant gains in student place attachment and place meaning. They recommended that application and innovation of psychometric measures of sense of place merit continued study.van der Hoeven Kraft et al. (2011) noted that *identity* is intertwined with the ideas of motivation, emotion, and individuals' connection to Earth. Cohn et al. (2014) articulated the value of interconnectedness and resilience within Native American communities as integral parts of understanding Earth systems. Ward et al. (2018) reported that Native American students cited family responsibilities and being close to home as reasons for choosing research opportunities that emphasize place and community. Both studies underscore that emotional connection with place and community, aspects of identity, coincide with cognitive engagement in geoscience content (Region 7 of Figure 1). Conversely, students' unfamiliarity with place, specifically the degree of novelty (Orion & Hofstein, 1994) can negatively affect the learning. Riggs (2005) noted that one of the most powerful strategies for teaching geoscience to Native American communities is the use of local field environments, especially lands that have been occupied and managed by Indigenous people for generations. The emotions attached to one's personal values and experiences are overlapping with the societally-relevant topics associated with the geosciences, such as natural hazards, economic natural resources, and climate change. Recent studies demonstrate that providing ways for learners to express their emotional sense-making can be improved (Hufnagel, 2015, 2017). Additional evidence of the tradeoff between emotional engagement with aspects of students' identity and cognitive engagement, where positive or negative emotional engagement promotes or inhibits cognitive engagement, is needed to advance our understanding of how these dimensions interplay within the Sinatra et al. (2015) framework and our model. van der Hoeven Kraft et al. (2011) also applied the concept of *interest* to the geosciences. The psychological constructs of interest (Hidi & Renninger, 2006; Renninger et al., 2014; van der Hoeven Kraft, 2017) and task value (Eccles, 1983; 2005) are important components of emotional engagement that drive an individual's motivation to continue engaging with a concept or experience. For example, transformative experiences promote emotional engagement through motivation and experiential value (Pugh, 2011). The educational psychology literature documents how these constructs influence conceptual change (Johnson & Sinatra, 2013; Sinatra & Pintrich, 2003) and learning strategies (Liem et al., 2008), both of which are germane to the GER community. One example that leverages educational psychology constructs in GER is Littrell et al. (2020) study of student engagement in a place-based environmental science program. Littrell et al. (2020) report on an informal science program for middle and high school students who generated a short film on a place-based environmental challenge. As an informal science program, students chose to engage in the program (behavioral engagement) and drove the topic and audience of the film (agentic engagement). The authors report that students had transformative experiences with the climate change concepts (emotional and cognitive engagement) placing their study within Region 13 of Figure 1. Similarly, Pugh et al. (2017a) demonstrated middle school students achieved conceptual gains when teachers enacted strategies designed to promote transformative experiences in a unit on weather.

The examples above document effective ways to incorporate theoretical constructs from psychology into GER. Huguet et al. (2020) provided an example of an active learning study which tested a set of active learning strategies (e.g., flipped classroom strategies, peer-to-peer teaching, and real-world context group activities) within a geoscience course to promote motivation. Following implementation of the active learning modules, a program evaluation survey revealed high levels of motivation, positive experiences collaborating with peers, and confidence in expressing their knowledge and finding alternative solutions to new problems. While this study employed only two items to measure intrinsic motivation rather than a research-validated instrument, the themes discussed by the authors suggest the intervention targets Region 12 of Figure 1 because students report ownership over their learning (agentic engagement), increased trust and commitment to collaboration (emotional engagement), and increased transferrable skills (cognitive engagement). McNeal et al. (2014) used skin conductivity as a proxy for measuring emotional engagement, and recommended that such data, coupled with journal entries and student dialogue, be used in courses to better assess and address teaching emotionally challenging topics. Such investigation would occupy overlapping regions of emotional and behavioral engagement (Region 7 of Figure 1).

Cognitive engagement in the geosciences

Cognitive engagement includes investment in learning and employing strategies that lead to deeper learning (Region 3 of Figure 1). These include the use of analogical thinking, models, sketching, and gesturing. Analogical thinking is particularly important to understanding large temporal or spatial scales of Earth processes (Cheek et al., 2017; Czajka & McConnell, 2018; Karlstrom et al., 2008; Resnick et al., 2017a, 2017b). Jee et al. (2010) placed the use of analogy in geoscience education within the theoretical framework of structure mapping (Gentner, 1983; Gentner & Markman, 1997) in which learners understand new information by drawing analogies to previous knowledge. Sibley (2009) extended this idea by proposing that instructors can help students increase their ability to understand scientific models through the same kind of knowledge construction used in analogical thinking. Specifically, he reasoned that students transfer inferences made about the model to the targeted phenomena by building on prior knowledge of the model. Therefore, new knowledge manifests as a change to students' schema—distinct mental representations that are held in working memory.

Multiple GER studies have reported on learning gains resulting from instruction with different types of models. Using a simple physical model involving flashlights and spheres to model seasonal changes, Gray et al. (2010) demonstrated a medium effect size of 0.48 (Cohen's *d*) on learning. Other studies using more complex physical models (Claiborne & Miller, 2012; Gray et al., 2011; Hubenthal, 2018) also provide statistically significant evidence of learning gains in addition to evidence of intensified student interest in the subject matter and motivation to conduct further inquiry (Mackin et al., 2012). These provide illustrative examples of studies in Region 7 of Figure 1 with overlapping cognitive and emotional engagement dimensions. Other types of models, including computational models (Bice, 2001, 2006; Kirchner et al., 2018), demonstrations (Arthurs, 2019), and classroom experiments (Coştu et al., 2010; Soja, 1999), are similarly used in geoscience classrooms to increase cognitive engagement. Luo et al. (2016) demonstrated a large effect size of 1.06 (Cohen's *d*) using a simulation for teaching landform development and evolution with a group of college students in a physical geography lab. An attitudinal survey conducted in conjunction with the simulation found that that students favored the simulation over traditional paper-based material. An effective method for increasing students' cognitive engagement in modeling activities is to ask them to make predictions, run the model, and evaluate their predictions based on model performance. These cycles of prediction and feedback are effective because they elicit students' existing mental representation (Liew & Treagust, 1995; Monaghan & Clement, 2000; White & Gunstone, 1992), closely mirror the work of experts (Shipley & Tikoff, 2017), and build students' conceptions of the authentic process of science (Dolphin et al., 2018).

Augmented Reality (AR) Sandboxes have become a popular physical model used to engage students both kinesthetically and visually with the relationship between contour lines and topography. Giorgis et al. (2017) investigated whether an AR sandbox intervention improved student interpretation of topographic maps in a large introductory geoscience course with control and experimental groups. Students were assessed post-instruction using a topographic map assessment, however, no significant learning gains were found. More recently, a study by Jackson et al. (2019) replicated these results with 730 students enrolled in an introductory geology course who were divided between experimental (used the sandbox) and control (did not use the sandbox) groups. Again, no significant differences in student learning were found. However, self-reported engagement was significantly higher in the experimental group (demonstrating a large effect with Cohen's d=.76) and was revealed to be a significant predictor of student learning as measured by the post-test, although the authors cite significant limitations with drawing meaning from this data. The authors suggest that the novelty of the AR sandbox was immediately apparent in students' emotional response (e.g. enthusiasm, positivity, and general enjoyment of playing with the AR sandbox; emotional engagement) and may have distracted students from learning or retaining information (i.e., cognitive engagement). Like Orion and Hofstein's (1994) caution of the potential negative effect of unfamiliar place, it is worthwhile to consider how the novelty of models may influence learning and investigate this unique response within the overlapping dimensions of cognitive and behavioral engagement (Region 7 of Figure 1).

Gesturing and sketching are additional examples of the overlap between cognitive and behavioral engagement (Region 14 of Figure 1). Both provide learners with a way to offload information and reduce cognitive load, thereby facilitating cognitive engagement with increasingly complex concepts (Mayer, 2014; Roth, 2001). Kastens et al. (2008) suggested that instructors structure learning with opportunities for students to grapple with spatially intensive concepts through gesturing as a way to indicate shape, position, orientation, relative size, and trajectories through space. Subsequent research analyzed student gestures as a way to understand the depth of student geoscience understanding (Alles & Riggs, 2011; Herrera & Riggs, 2013; Van Boening & Riggs, 2020). Less research has evaluated gesturing as an instructional intervention for facilitating learning spatially challenging geoscience concepts. One exception is a study by Atit et al. (2015), which confirmed the value of engaging students in gesturing with a medium effect size of 0.09 (partial eta squared), especially with improving penetrative thinking (i.e., the ability to visualize and reason about the interior structure of an object based on what is visible on the surface).

The research basis for introducing sketching into undergraduate geoscience courses rests on work done by Mayer (2014) who demonstrated that students learn best when simultaneously interacting with pictures and accompanying textual explanations. Several studies demonstrate the value of sketching for understanding geoscience phenomena (Forbus et al., 2011, Forbus et al., 2018; Gobert & Clement, 1999; Jee et al., 2014; Johnson & Reynolds, 2005; Ormand et al., 2017; Reusser et al., 2012; Reynolds & Peacock, 1998; Smith & Bermea, 2012; Steer et al., 2005). With increasing evidence suggesting that sketching and gesturing can increase cognitive engagement and propel active learning in students, Ormand et al. (2017)—a research team composed of geoscientists and cognitive psychologists—collaborated to develop two dozen spatial learning activities for mineralogy, structural geology, and sedimentology and stratigraphy courses. Pre- and post-test scores on four spatial thinking instruments showed statistically significant improvement and Cohen's d values indicated that students were making moderate to large improvements with spatial thinking skills ($d = 0.5 - 1.1$). Uttal et al. (2013) discussed the potential for recruiting and retaining STEM students as a consequence of spatial training. As more geoscience instructors adopt these strategies, future studies should investigate how cognitive engagement in spatial thinking interacts with emotional and behavioral engagement (Region 7 and 14 of Figure 1, respectively), specifically with respect to persistence in STEM.

The studies reviewed above are disproportionately focused on visual-spatial aspects of cognitive engagement and are not exhaustive of the broader educational psychology literature on cognitive engagement. For example, connected learning research leverages "interest-driven" and "socially-embedded" engagement to cultivate cognitive engagement (Ito et al., 2013). This research paradigm promotes equity and engages multiple dimensions of engagement to foster deep learning strategies. Expanding the scope of GER research on cognitive engagement beyond visual-spatial dimensions is fertile ground for growth.

Agentic engagement in the geosciences

Agentic engagement occurs when students actively contribute to the flow of instruction, which naturally occurs in many active learning scenarios such as inquiry-based learning, discovery learning, or student investigations (Region 4 of Figure 1). Research on conceptual change suggests that when students exercise control over their learning they will have high levels of engagement because they are motivated (Bereiter, 1990; Dole & Sinatra, 1998). Because learning is effortful (Strike & Posner, 1992), students must be engaged as intentional learners (Bereiter, 1990), who learn because they are driven to answer their own questions rather than simply completing an academic task. Laboratory learning and inquiry-based learning set up the conditions within which students can exercise agency over their learning. Experiments are an essential component of some sub-disciplines in the geosciences. For example, geochemists use a variety of laboratory and analytical instruments to investigate the origin and evolution of Earth materials, and then broadly apply their findings to Earth's systems. In geoscience classrooms, this investigative process is underrepresented in lab manuals that consist primarily of exercises that confirm previous learned concepts (Ryker & McConnell, 2017). However, classroom observations demonstrate that faculty and graduate teaching assistants capably teach modified lab exercises that increase levels of student inquiry and promote enhanced agentic engagement (Ryker & McConnell, 2014). As one example, Maria et al. (2011) reversed the typical sequence of lecture and lab in petrology classes and rather than introducing and describing phase diagrams during lecture, designed a laboratory exercise for students to generate their own phase diagrams from student collected data using differential scanning calorimetry. This process allowed students to conceptualize possible origins for different rock types and form predictions using observed thermodynamic processes. This paralleled observation-prediction cycles described by Shipley and Tikoff (2017) by allowing students to develop models that they could test against predictions. In this case students drove the process and therefore exercised agency over their own learning, exhibiting an example of a study situated in Region 4 of Figure 1. The authors report mastery-level performance on the laboratory and positive student attitudes, situating this study in Region 12 of Figure 1.

Another example of a well-guided inquiry-based lab is described by Grundstein et al. (2011), who had students play the role of a forecaster, analyze meteorological data for a severe weather event, provide diagnostic and prognostic discussions of the atmospheric environment, and predict the potential for severe weather. Grundstein et al. (2011) documented that students reported positive emotional engagement in laboratory learning, providing a nice example of a study located in Region 15 of Figure 1.

Few studies focus on agentic aspects of course-based field trips and field camps. Todd and Goeke (2012) discussed the impact of incorporating a capstone field trip where students are charged with leading a component of the field learning based on a particular site. This may be an ideal example of how students can be engaged in co-constructing learning. Petcovic et al. (2019) interviewed 67 geologists about how they learned to do bedrock mapping, a skill that is taught almost entirely in field camp settings. Their participants reported that working in peer groups, learning from mentors, and teaching others were influential experiences to learning to map—all of which have a component of agentic engagement and would occupy Region 8 of Figure 1. Overall, inclusion in a community of practice was considered a crucial contributor to co-constructing learning. Certainly, studying the relationships between cognitive, agentic, behavioral, and emotional engagement in field-based learning is essential for the geosciences community to understand its overall benefits.

Recommendations

This model of active learning in the geosciences (Figure 1) supports existing efforts to define the grand challenges of

GER (St. John et al., 2021). One of the recommendations from the *Community Framework for Geoscience Education Research* suggests that *"future GER should be better grounded in theory"* (St. John [Ed.], 2018, p. 144) The model we propose provides a step in that direction (see Recommendation #1 below). Additionally, there is need for studies, within and beyond GER, that compare active learning strategies. For example, what are the relative benefits of engaging students in sketching (Forbus et al., 2018) versus classroom response systems (e.g., clickers; LaDue & Shipley, 2018)? What are the impacts on persistence in the geosciences for interventions that build spatial skills (Gold et al., 2018) versus building self-regulation strategies (van der Hoeven Kraft et al., 2014)? The capacity for GER or any DBER community to answer these and other research questions hinges upon the quality of the community metrics (see Recommendation #2 below). Presently, there is a shortage of research-validated, quality assessments in all of the engagement dimensions. This hinders researchers' ability to conduct the meta-analyses necessary to propose a robust theory of active learning. The *Community Framework* suggests that *more attention needs to be given to assessment to insure the more valid, reliable, and up-to-date instruments and techniques are used in GER* (St. John [Ed.], 2018, p.145). In order to accumulate evidence and gauge the strength of that evidence in GER (St. John & McNeal, 2017), the GER community must also document their methods and results carefully (see Recommendation #3 below). The GER community is currently engaged in large scale efforts to improve teaching practice, which includes incorporating active learning strategies (Manduca et al., 2017; Teasdale et al., 2017; Viskupic et al., 2019). This is an opportunity to measure active learning impacts high on the *Strength of Evidence Pyramid* since it involves multiple institutions and instructors (St. John & McNeal, 2017). There is also a need for more studies that examine disciplinary learning beyond the general education classroom setting. Much of the extant active learning literature focuses on introductory learning and less is known about expertise development at the upper-division or graduate level, where DBER research can be most beneficial as it is grounded in disciplinary knowledge (see Recommendation #4 below). Viewing these needs and opportunities through a lens of engagement, we make four recommendations for future work on active learning in the geosciences:

Connect GER to our model of active learning in the geosciences

Existing active learning research studies are emergent from higher education classroom practice but loosely apply educational psychology theories that have a longer history of investigation (Mintzes, 2020). Future research on active learning strategies should be grounded in existing frameworks of engagement (Chi & Wylie, 2014; Sinatra et al., 2015) and foundational learning theories that take into account psychological factors such as motivation, identity, and sense of belonging (Bandura, 1986; Eccles,1983; Lave & Wenger, 1991; Pintrich & De Groot, 1990). This model for active learning in GER incorporates research from the broader literature and is built upon a framework (Sinatra et al., 2015) that can ensure GER research not only accumulates evidence within GER but connects to research being conducted across other discipline-based education research communities.

Measure more than content learning

The most serious limitation to the accumulation of evidence for active learning is measurement. Extant studies usually leverage more than one dimension of engagement, but outcome measures often focus on learning gains, which are measured in the form of course grades, DFW rates, or gains on concept inventories (Freeman et al., 2014; Theobald et al., 2020). Certainly, the goal of an undergraduate science course is to cultivate learning more broadly. Nevertheless, issues of emotional, behavioral, and agentic engagement can feedback into subsequent learning gains if students persist in the discipline (Bandura, 1986). The geosciences have several existing instruments from which to draw when designing GER studies of active learning (National Association of Geoscience Teachers, Geoscience Education Researcher Toolbox, National Association of Geoscience Teachers Web Site, 2019).

Research validated measures of geoscience content learning include the Geoscience Concept Inventory (GCI; Libarkin & Anderson, 2005), the Landscape Identification and Formation Test (LIFT; Jolley et al., 2013), the Landscape Perception Test (Iwanowska & Voyer, 2013), and the Moon Phase Assessment Instrument (Rivet & Kastens, 2012). Other useful tests include tests of geoscience spatial skills, specifically, bedrock cross-sectioning (Ormand et al., 2014) and sense of scale (Tretter et al., 2006). These measures may serve as indirect indicators of cognitive engagement, but do not describe the learning process (e.g., elaboration, sketching, etc.) during which cognitive engagement is occurring. Geoscience-specific measures of emotional engagement include measures of novelty space (Elkins & Elkins, 2007; Orion, 1989), beliefs and attitudes about climate change (Chryst et al., 2018; Maibach et al., 2011), and perceptions of Earth sciences (Jolley et al., 2012). A promising line of research emerging in the geosciences is to use behavioral engagement as a way to measure cognitive engagement (Kastens et al., 2016; Maltese et al., 2013; Siemens & Baker, 2012) and emotional engagement (McNeal et al., 2014), as well as to use behavioral engagement as a proxy for active learning implementation (Lane & Harris, 2015; Teasdale et al., 2017; Viskupic et al., 2019)

There is limited research on aspects of *learning to learn*, such as self-regulated learning (van der Hoeven Kraft et al., 2014) and other aspects of agentic engagement in learning, including field-based learning (Todd & Goeke, 2012). One understudied component of active learning in the geosciences is agentic engagement in research experiences. Since much of the active learning literature emerges from classroom practice, the most relevant type of research experiences are course-based research experiences, or CUREs. This is an area of burgeoning research, particularly in biology (Auchincloss et al., 2014; Bangera & Brownell, 2014; Brownell & Kloser, 2015; Corwin et al., 2015), community college settings (Hewlett, 2009) and non-majors' courses (Ballen et al., 2017). Students in introductory geology classes students shifted from triggered to maintained situational interest after engaging in a CURE (Kortz & van der Hoeven Kraft, 2016). Students who participated in a National Weather Center REU were significantly more committed to attend graduate school at the end of the program (Gonzalez-Espada & LaDue, 2006). In upper-division experiences for students, Research Experiences for Undergraduates (REUs) have supported students into making major degree path changes which would indicate a shift into individual interest (Jarrett & Burnley, 2003). A number of outstanding research questions have yet to be investigated in the geosciences. Those raised by Ballen et al. (2017) focus on comparing CUREs enacted with majors versus non-majors, and focus upon examining the interplay between dimensions of agentic, emotional, and cognitive engagement. Brownell and Kloser (2015) provide an excellent review of assessments that evaluate a variety of dimensions of student engagement in CUREs.

An important consideration for measuring active learning is the value of classroom observation protocols (Denaro et al., 2021; Lane & Harris, 2015; Smith et al., 2013, 2014; Teasdale et al., 2017; Viskupic et al., 2019). These provide an opportunity to measure fidelity of implementation and tease apart the source of the impact of any implementation. For example, a national study of over 1,100 students in introductory geology courses at 17 different institutions of varying types found 9% of the variance of student grade was attributable to the instructor, over a third of which was due to the instructor strategy (van der Hoeven Kraft et al., 2014). Participants in this study took both the pre- and post- Motivated Strategies Learning Questionnaire (MSLQ; Pintrich et al., 1991) in conjunction with the Reformed Teaching Observation Protocol (RTOP) (Budd et al., 2013). There was a strong correlation between student expectancy for success with the instructor strategy, suggesting that more student-centered instruction can impact those students who enter the geoscience classrooms with lowered motivation (van der Hoeven Kraft et al., 2014). This research design included measurement of classroom strategy through observation protocols, as well as gains on instruments beyond conceptual learning, to provide a deeper understanding of the value of teaching strategy (van der Hoeven Kraft et al., 2014). RTOP has been used most extensively in the GER community to directly observe undergraduate classes (Teasdale et al., 2017; Viskupic et al., 2019). Lane and Harris (2015) Behavioral Engagement Related to Instruction (BERI) and Smith et al. (2013, 2014) Classroom Observation Protocol for Undergraduate STEM (COPUS) are also validated classroom observation protocols that could aid in documenting student engagement for active learning studies aligned with the model we present here. COPUS has been widely used in other DBER fields and requires minimal training to yield high reliability.

Overall, the outcome measures associated with various types of engagement are vital to understanding active learning and accumulating evidence. The broader research community should consider expanding the scope of outcome variables measured to document the feedbacks between dimensions of emotional, behavioral, cognitive and agentic engagement and document how an active learning strategy is enacted in the classroom (Figure 1).

Document research methods and outcomes with effect sizes to improve strength of evidence

Throughout the examples presented above, we include whether the study reports findings of significance coupled with effect sizes, if they were reported in the research. Effect size determines whether the results of a particular analysis are statistically *meaningful* (Coladarci et al., 2008), while p-value determines whether results are statistically *significant*, which is highly dependent on sample size (Thompson, 1998). As such, determining if a sample is statistically significant simply tells us the two populations are different, but not the degree or magnitude to which those differences exist (Coe, 2002). The power of the effect size, is that it allows one to move beyond, "is it effective," to "how effective is it?" (Coe, 2002). It should be noted that Cohen's *d*, the most common of effect size, is dependent on a normal sample distribution. Examples of other effect size measures are discussed earlier and gauge the efficacy of studies with varied samples and analyses. Reporting effect sizes is becoming a more common practice in the geosciences, particularly in papers published in the research category of the *Journal of Geoscience Education*. We recommend a community-wide effort to document means, standard deviations, and sample sizes for all studies reporting on interventions in order to calculate effect sizes. This enables the research community to generate community-wide meta-analyses similar to those reported in Freeman et al. (2014) and Uttal et al. (2013), which demonstrate the collective progress and gain in understanding for discipline-wide challenges. Furthermore, they enable the GER community to determine the relative value of various active learning strategies (Hattie, 2015).

In order to increase the generalizability of findings on the effectiveness of active learning strategies, cohort studies conducted across multiple instructors and institutions are needed (St. John & McNeal, 2017). Despite a growing population of adopters, the GER evidence base has not kept pace (Semken et al., 2018) and availability of activities that incorporate active learning strategies (e.g. Teach the Earth) is not enough by itself to drive a community to large-scale change (Henderson et al., 2011). The GER community strongly endorses the idea that claims about teaching practices should be evidence based and that the strengths and limitations of research claims should be transparent (St. John & McNeal, 2017).

Prioritize research on active learning that emphasizes the interplay of engagement dimensions that are essential to the geosciences

With introductory, large-lecture courses, many of the same strategies enacted across DBER fields are useful in the geosciences (Arthurs & Kreager, 2017; McConnell et al., 2017). However, there are aspects of active learning in the geosciences within and beyond the classroom that are relatively unique in terms of the interplay between different dimensions of engagement. We did not find exemplary studies that involve the interplay of behavioral, cognitive, and agentic (Region 9, Figure 1), for example. Many geoscientists were inspired by early experiences with volcanoes, oceans, fossils, or the weather (Hoffman et al., 2017; Houlton, 2010; LaDue & Pacheco, 2013; Levine et al., 2007; O'Connell & Holmes, 2011; Pugh et al., 2019; Sexton et al., 2018; Wolfe, 2018) indicating that emotional engagement is paramount to participation in the geosciences.

Similarly, there are aspects of emotional engagement that are negative. The discipline also suffers from an image problem as it is viewed as a science done only outdoors (O'Connell & Holmes, 2011), in white spaces (Sexton et al., 2014) which may be unappealing or inaccessible for some communities. Issues of equity and inclusion go beyond the classroom in the context of field-based and place-based learning (Carabajal et al., 2017; Gilley et al., 2015; Hendricks et al., 2017; Ward et al., 2018). This can deter people who do not see themselves represented in the discipline (Bernard & Cooperdock, 2018; Hartten & LeMone, 2010). As a found major, many students discover the geosciences through an introductory course (Stokes et al., 2015), and as such community colleges are an important entry point into the geosciences (Wolfe, 2018). Students in an introductory geology class at community college reported lower incoming self-efficacy compared with those at research intensive university (van der Hoeven Kraft, 2014), suggesting we need creative approaches to increase engagement in the geosciences. Additionally, early experiences with Earth science instruction focused on cookbook labs and rock identification may also fail to capture the excitement of modern Earth science questions and methods (Ryker & McConnell, 2017) and belie the place-based and societal relevance of the geosciences.

Within and beyond the classroom, the GER community must attend to measuring the emotional and behavioral dimensions of engagement in geoscience classrooms, laboratory, and field-settings to understand persistence. Furthermore, a lack of learning gains does not constitute an unsuccessful active learning intervention if it leads to greater persistence long-term. One opportunity for deepening GER on engagement is conducting person-centered analyses (Snyder & Linnenbrink-Garcia, 2013), which provides rich descriptions of the interplay of multiple dimensions to elucidate the mechanisms by which people learn (Pugh et al., 2017b). Research into the effectiveness of specific active learning strategies in the classroom and beyond as well as long term impacts of various strategies are imperative to solving the grand challenges for our discipline (St. John, 2018).

Summary

The illustrative narrative presented earlier, involving Jessica, provides an example of how all four dimensions of engagement are at play during the learning process (Figure 1, Region 13). The model of active learning in the geosciences we propose is grounded in the educational psychology literature (Sinatra et al., 2015) and highlights how active learning research studies investigate learning that involves multiple dimensions of engagement. Currently, many active learning research studies focus on knowledge gains as measured by concept inventories, exam scores, or course grades. These may be a proxy for cognitive engagement, however, as we see in the example of Jessica, there are often multiple engagement dimensions at play that could influence performance on one of these measures. Measuring emotional, behavioral, and agentic engagement can provide a richer context for understanding of the relative value of active learning strategies. Likewise, robust observation of cognitive engagement can illuminate the mechanisms by which particular strategies work.

Built upon existing theory from educational psychology, this model for active learning in the geosciences presents a structure for designing and measuring active learning strategies. The model aligns with recommendations made in *Community Framework for Geoscience Education Research* (St. John [Ed.], 2018) and supports the accumulation of evidence needed to progress along the Strength of Evidence pyramid (St. John & McNeal, 2017). Of particular importance is the need to develop methods for measuring the various dimensions of engagement. One GER community strategy is to leverage instruments and methods utilized beyond the GER community (e.g., educational psychology, other discipline-based education research fields). Four recommendations will enable the GER community to build stronger active learning research: (1) the use of this theory-grounded model of active learning, (2) thoughtful measurement of the dimensions of engagement, (3) documenting methods and metrics of assessment to accumulate evidence, and (4) prioritize aspects of active learning that uniquely enhance geoscience learning. Through the collaborative, transdisciplinary efforts of researchers from the education psychology and science communities, we can clarify the curious construct of active learning.

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ORCID

N. D. LaDue http://orcid.org/0000-0002-0954-4034
P. M. McNeal http://orcid.org/0000-0002-3461-011X
K. Ryker http://orcid.org/0000-0002-3781-3422
K. St. John http://orcid.org/0000-0001-7045-7485
K. J. van der Hoeven Kraft http://orcid.org/0000-0003-0848-3345

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