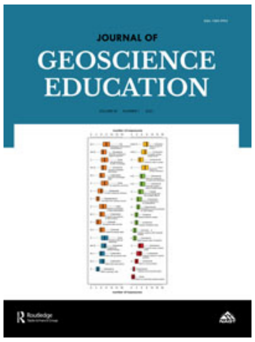

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Self-regulated learning: Overview and potential future directions in geoscience

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ABSTRACT
Self-regulated learning (SRL) models provide a framework for understanding the observed variance of student performance in geoscience learning contexts. Instructors can potentially use a SRL framework to support students in self-identifying the specific approaches to learning they use when engaging in geoscience learning situations (coursework, field experiences, visualization and abstraction tasks, etc.) and guide them in adopting more effective learning strategies and tactics, ultimately improving their performance and learning. Presented here is a summary of a SRL theoretical framework from the educational psychology community, an overview of recent research in science learning at the college-level using SRL frameworks, and recommendations for future SRL research directions in geoscience to promote SRL in teaching and learning practices.

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Student learning; theoretical frameworks; college geoscience teaching; self-regulated learning

Introduction

There are many factors that can influence student learning in geoscience courses. There are differences between students such as age, gender, and previous experience. There are also many course context factors such as content, types of academic tasks, class format (e.g., face-to-face vs. online) and the reward structure (e.g., points for effort, assessment types). Finally, the nature of instruction itself can contribute to learning outcomes. Despite this, there are students in similar environments with similar characteristics and prior experiences that demonstrate significantly different results. Also, there are students who should be well placed to succeed that perform poorly, while others overcome challenges to earn a high grade. As a result, one may ask, "why do some students succeed, and others do not?" A large body of research in educational psychology has investigated this phenomenon and provided the theoretical framework of self-regulated learning (SRL) to explain some of the disparities in student outcomes. Generally speaking, SRL refers to the systems of decisions and behaviors a student employs to accomplish a learning task (Zimmerman, 1990). Copious investigation into SRL within an education psychology context has correlated effective SRL decisions and behaviors to increased learning (Panadero, 2017).

Relatedly, the National Research Council (NRC, 2012) and others have called for discipline-based education researchers to recognize the interdependence of cognitive (information processing) and affective (emotions, attitudes, etc.) processes related to self-regulated learning as a critical way to improve performance and persistence in STEM. In the geoscience education community specifically, McConnell and van Der Hoeven Kraft (2011) identified the critical role affect and self-regulated learning (self-management of learning strategy use) processes play in students' use (or non-use) of effective cognitive strategies when learning geoscience. Additionally, SRL has recently been identified as a critical research theme and grand challenge for the future of geoscience education research (McNeal et al., 2018; St. John, 2018) and broadening participation in geoscience.

Why is a self-regulated learning model so important to the future of geoscience education? Consider a typical introductory geoscience class in which some students are high performing and others are not. SRL offers researchers and instructors a conceptual framework for understanding student learning and in turn student success (or failure) in a way that bridges affective, cognitive, and metacognitive domains. Instructors can use a SRL framework to identify specific student approaches to class assignments across these domains and guide students in adopting more effective learning strategies and tactics.

But what is the nature of student SRL in a typical geoscience classroom setting? What tools and strategies can be used to characterize a student's unique approach to SRL? How can instructors influence these student self-regulatory processes to positively impact student learning outcomes? While SRL has been a topic of interest in the educational psychology community since the 1970s (see Zimmerman & Schunk, 2011 for an overview), self-regulated models of learning have remained largely unexamined in college-level geoscience classrooms. To facilitate an expanded discussion of these issues within the geoscience education community

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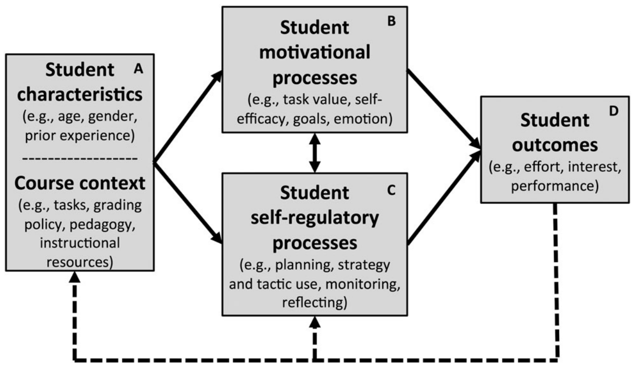

Figure 1. Theorized role of self-regulation in student outcomes (adapted from Zusho et al., 2003).

and more broadly in DBER, the goals of this paper are to (1) provide a theoretical framework for SRL with an overview of current SRL models that can be used to situate future investigations; (2) explain how SRL processes have been documented and supported across STEM disciplines to facilitate student learning; (3) provide a roadmap that identifies previous work in this area, gaps in our understanding, and guidelines and suggestions for future directions of SRL work in geoscience, specifically. This review is needed so that SRL models and tools can be used by researchers and instructors to improve student learning outcomes in the geosciences and to provide students with strategies that can be applied to help deepen learning in future courses. Additionally, we seek to ground consideration of SRL firmly within a geoscience context throughout this work via practical examples (fictional vignettes) to help facilitate understanding of the concepts described.

Review methods and timeframe

One of the primary goals of this paper is to provide a conceptual framework for SRL in post-secondary science settings. SRL frameworks are relatively contemporary, beginning in the 1980s and producing a series of critical studies in the next two decades (e.g., Zimmerman, 2000). Work from these early SRL frameworks are considered the foundational models of SRL and the basis of much of the work since, consequently, our review focuses on the exploration of the literature from these early works to the present.

While rooted in psychology, SRL is more recently being explored in discipline-specific contexts, including in geoscience. To capture a wider DBER lens of applied models of SRL, which potentially have more implications for future geoscience education community work on this topic, we reviewed articles from key journals in the Physics Education Research, Chemistry Education Research, and Biology Education Research communities from 2000 to present. The Geoscience Education Research (GER) community is relatively young and may be considered emerging compared to some other DBER fields (McConnell, 2019; NRC, 2012). Our review of research on SRL in geoscience started with the Earth and Mind book collections (Kastens & Manduca, 2012; Manduca & Mogk, 2006), the outputs of the community conferences on the role of the affective domain (SERC, 2007) and metacognition (SERC, 2008), and a survey of geoscience work published within the *Journal of Geoscience Education* since 2006. Additionally, because we are exploring SRL in a post-secondary science context, we only included studies that involved participants in a post-secondary and discipline-based setting.

Groundwork for investigating SRL in geoscience contexts

While formal investigation into SRL behaviors of students in geoscience courses is in its early stages, the GER community has focused on related questions. Though each did not consider SRL directly, the GSA Special papers *Earth and Mind* (Manduca & Mogk, 2006) and its successor *Earth and Mind II* (Kastens & Manduca, 2012) brought attention to the relationship between cognitive and metacognitive components of learning in the geosciences and laid the groundwork for thinking about factors that affect student experiences in geoscience courses outside of the content itself (e.g., spatial skills).

Around the same time as Earth and Mind I, the geoscience education community began to place emphasis on the affective domain. The affective domain is broadly considered as the "interests, attitudes, appreciations, values, and emotional sets or biases" of learners that influence learning (Krathwohl et al., 1964). Through seminal workshops (2007, 2009) facilitated by the *On the Cutting Edge* project and scholarly works elucidating the concept of the affective domain and its role in geoscience learning (McConnell & van Der Hoeven Kraft, 2011; van Der Hoeven Kraft et al., 2011), the exploration of the affective domain in the geosciences provided the foundation for the consideration of student variables and their role in the geoscience learning process.

This early inquiry into the affective domain in the geosciences led to a group of researchers to collaborate in creating the Geoscience Affective Research NETwork (GARNET) to investigate student affect in introductory geology courses at a variety of institutions. Within the larger push toward characterizing student affect via constructs such as emotion, motivation, and connections to Earth, GARNET research also included components that were associated with SRL (particularly metacognition) and suggested that these components may be easier to facilitate in the introductory geology classroom via the integration of cognitive and metacognitive strategies into course assignments (Gilbert et al., 2012; Lukes & McConnell, 2014a, 2014b; McConnell & van Der Hoeven Kraft, 2011; van Der Hoeven Kraft et al., 2011). Finally, van der Hoeven Kraft (2017) provided a theoretical framework for characterizing and potentially cultivating interest in the geosciences and highlighted the construct of interest as an influence on SRL with interested students more likely to exhibit effective SRL behavior and vice versa. In our analysis below, we will seek to distill the theoretical underpinnings of SRL and synthesize prior investigations in college science settings.

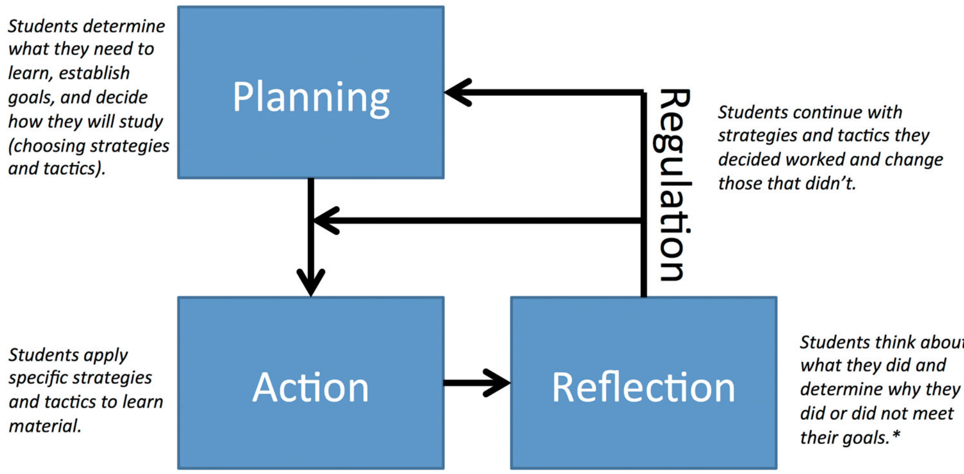

Figure 2. General composite model of self-regulated learning (adapted from Zimmerman, 2000).

Analysis

SRL models seek to explain why some students are successful and others are not. SRL was originally theorized as applied social cognitive theory (Bandura, 1986) in educational contexts (Zimmerman, 1990). In these SRL models of learning, self-regulation and motivation are thought to mediate the relationships between students, the classroom context, and student learning outcomes (Pintrich, 2000; Pintrich & Zusho, 2007; Winne & Hadwin, 2008; see Figure 1). The effects of differences between students' characteristics and the classroom environments they experience therefore may influence outcomes, but may not have a direct causal relationship. Instead, differences in the individual prior experiences of students and the nature of classroom contexts influence student motivation as well as how they plan and implement learning strategies (self-regulation), which in turn influences outcomes. So, any observed differences in student outcomes by age, gender, instructional methods, etc. are the result of the motivational and self-regulatory strategies and processes a student employs to complete learning tasks (Figure 1). Therefore, the more we can shape the learning environment to help students become better self-regulators, the more likely it is that students will become more skillful learners.

What is self-regulated learning?

Despite some structural differences between commonly used models of SRL (e.g., Pintrich, 2000; Winne & Hadwin, 1998, 2008; Zimmerman, 2000), there is consensus on the underlying assumptions that define the nature of self-regulated learning (see Pintrich, 2000). First, SRL is an active, constructive process. Students are agents, taking ownership of the learning process and making meaning of themselves and their environments. Second, students set goals for their learning, so that learning is a goal-driven process. Third, students attempt to manage their thinking (i.e., cognition), motivation, emotions, and behavior through a series of monitoring and control processes, as dictated by their goals and the learning environment (Pintrich, 2000).

Successful self-regulated learners think about how they process information and how their learning directs their engagement: they are metacognitively aware of their learning processes. The concept of metacognition refers to the interface between a learners' awareness and their underlying brain function (or *cognition*; Flavell, 1979). Metacognitive awareness allows them to reflect on how their learning outcomes compare to internal and external standards. For example, when reading a page in a textbook about igneous rock formation, a student who is metacognitively aware recognizes when they do not understand the text they are reading by comparing their perceived performance to internal standards. They may also recognize when they do not understand the specific concepts in the reading that will be on the test by comparing their perceived performance to external, instructor-provided standards of the test such as a practice test or a list of learning objectives. For example, they may miss a homework or practice test question that asks them to predict the crystal size of an igneous rock if the magma in question cooled slowly and thus recognize that they don't know how mineral crystal size is related to magma cooling rate.

Discrepancies between these standards and their learning outcomes may prompt students to reflect, evaluating the effectiveness of their learning strategies, and perhaps to identify alternative strategies (Winne & Hadwin, 1998). Ideally, the results of these self-evaluations lead to regulation and/or control of their learning behaviors. Regulation is the change and the adoption of more successful learning strategies and tactics, while control refers to attempts to focus effort and attention to more successfully implement learning strategies and tactics. If there are no discrepancies, students confirm the usefulness of their strategies and tactics and plan to continue to use them. For a more-thorough explanation of the role of standards in student self-assessment, see Winne and Hadwin (1998).

The principal assumptions outlined above can be structurally organized into a general, composite model of SRL (Figure 2). SRL is depicted as a recursive loop that links the commonly accepted macro-level student processes as phases: planning, action, reflection, and regulation (e.g., Greene &

Azevedo, 2009). In the planning phase, students define the learning tasks, establish goals, and choose strategies and tactics to achieve those goals. These (and their variations) are examples of micro-level SRL processes. For example, students may decide that they need to know the concept of the rock cycle so they can meet their goal of earning an A on the exam. They choose to accomplish this goal by selecting the tactic of re-reading their notes. In the second phase of SRL, students take action by employing their strategies and corresponding tactics (e.g., re-reading notes, choosing a quiet location so they can focus while reading). In the third phase, which may occur in tandem with the second phase, students reflect on the perceived success of their actions.

Reflection includes three sub-components: monitoring, evaluation, and analysis. Monitoring involves comparing what is being done to a standard or criterion. A student may monitor thoughts, feelings, and/or behavior, but often may not realize when they do, as this process often occurs covertly. For example, a student who looks at a rock cycle diagram may finish examining it and determine that they just read and didn't process the information. This realization, termed a feeling of knowing or a judgment of learning, is a product of the monitoring process (Dunlosky & Tauber, 2014). Evaluation occurs when a student compares monitoring results to learning goals. The student who read the diagram decided they did not meet their goal to be able to explain the parts of the rock cycle. Analysis then occurs when the student examines the monitoring and evaluation results to either affirm the usefulness of current tactics or determine if modifications and/or alternative strategies are needed.

In our example rock cycle case, the student may analyze the situation and conclude that they did not meet their goal to be able to explain the parts of the rock cycle because they were going through the physical motions of implementing the reading strategy, like eyes scanning the words, but did not attach meaning to the words. The realization that their learning goals have not been met may trigger the regulation phase in which the student seeks to improve future outcomes by changing their cognitive and affective tactics and/or adding control tactics to support their current learning strategies. For our example, the student may choose to change cognitive strategies and use a new tactic, such as sketching a diagram of the rock cycle. Or, the student may continue to re-read the rock cycle diagram, but add a control tactic, such as reading the diagram labels aloud to help them to focus and process information more effectively.

It is important to note that the composite model of SRL presented in Figure 2 is not meant to be inclusive of all the micro-level SRL processes (each of the major SRL models developed by education psychology researchers have their own imagining of potential subprocesses); nor is the model meant to imply that SRL is a strictly sequential pattern. Rather, the model is meant to emphasize that self-regulation is an iterative, recursive process and that "closing the loop" through regulation is key to achieving effective student learning.

Evidence for SRL models

Early SRL models (Pintrich & De Groot, 1990; Zimmerman, 1986, 1989), and thus the primary theoretical framework for SRL, were informed by the assumptions of social cognitive theory (self-regulation and motivation are thought to mediate the relationships between students, the classroom context, and student learning outcomes; Bandura, 1986). Later revised or extended models of SRL (Pintrich, 2000; Zimmerman & Moylan, 2009; Winne & Hadwin, 1998; 2008; Boekaerts, 2011; Panadero, 2017) were built on these original assumptions, potentially limiting their strength. Most SRL models emerged through iterative exploratory research methods primarily centered on self-report student interview and survey instrument data in psychology labs or courses. SRL-related survey instruments asked students to report on a Likert scale the degree to which they agreed with statements about their learning strategies and choices. Major instruments include the Motivated Strategies Learning Questionnaire (MSLQ; Pintrich & De Groot, 1990; Pintrich et al., 1993), the Learning and Study Strategies Inventory (LASSI; Weinstein & Palmer, 2002), and the Metacognitive Awareness Inventory (MAI; Schraw & Dennison, 1994). Though these instruments have been re-analyzed to test the validity and reliability of their constructs (e.g, Hilpert et al., 2013), such survey data is considered generally reliable for measuring global SRL, but not for its subprocesses (Rovers et al., 2019). Survey instrument tools have also been criticized for reliance on self-report, as self-report may not be accurate at certain grain sizes of approximation (Azevedo, 2009; Rovers et al., 2019; Winne & Jamieson-Noel, 2002). As such, think-aloud protocols and trace data sources (e.g., Azevedo, 2005, 2009; Duffy & Azevedo, 2015) have been used to inform the understanding of SRL models and provide increased validity and reliability (trustworthiness) to self-report data through triangulation.

What is metacognition and how is it related to SRL?

Integral to effective SRL behaviors is the concept of metacognition. Often over-distilled to the concept of "thinking about thinking," global metacognition is generally separated into two distinct theoretical sub-components: *knowledge of cognition* and *regulation of cognition* (Schraw, 1998). A learner may be metacognitively aware in regards to facets of one, the other, or both and may have unique strengths and weaknesses in each realm. *Knowledge of cognition* refers to information a learner knows about their own cognition or about cognition in general and *regulation of cognition* refers to the thinking that helps learners control their learning (Schraw, 1998). Similar to SRL, these sub-components of metacognition have been subdivided into categories or processes. While listing all of them is not within the context of this work, it is important to note three sub-processes of knowledge of cognition for future consideration of SRL. Metacognitive awareness attributed to knowledge of cognition can be either declarative (i.e., "I have a good memory"), procedural (i.e., "I know which study strategies I use") and/or conditional (i.e., "I have different study strategies for different situations"; Schraw, 1998). Finally, it is important to clarify the distinction between metacognition and SRL as they are often used interchangeably with one another (Dinsmore et al., 2008).

For our considerations in this paper, we adopt a theoretical relationship between metacognition and SRL similar to the Winne and Hadwin model of SRL (Winne & Hadwin, 2008) in that metacognition is the primary driver of regulatory processes. In other words, a student with metacognitive skills uses those tools to be effective at SRL. These metacognitive skills (internal thought processes of the student) are used to generate the regulatory behaviors that the student chooses to utilize during a study task. The greater the metacognitive awareness, the more efficient and successful the cycling of SRL planning, monitoring, and evaluation becomes. In this sense, the metacognition can be considered as an internal mental process that is utilized to generate outward (SRL) behavior. Therefore, effective metacognitive knowledge and skills are necessary prerequisites for effective SRL behaviors.

To ground this distinction in a practical geoscience example, consider two college students preparing for a mineralogy lab exam. Student A demonstrates metacognitive awareness while Student B does not. A week before the exam, Student A realizes the exam is near and that her knowledge of carbonates and evaporites is relatively weak, while her knowledge of silicates is much stronger. She uses this metacognitive information to inform a SRL behavior and generate a study plan (i.e., planning phase of SRL) that incorporates a greater emphasis on her self-identified problem areas (i.e., carbonates and evaporites) and less of a focus on concepts she is more confident about. During her study, she self-tests her knowledge of carbonates and evaporite minerals by generating flash cards for each of the carbonate and evaporite minerals featured in her lab (i.e., monitoring phase of SRL) and reevaluates her knowledge level on these groups as her performance improves. In this scenario, Student A's metacognitive awareness and conditional knowledge of what strategies and tactics to use directly influenced the features of her study practice during the planning, monitoring, and regulation phases of the SRL cycle she utilized to prepare for the exam.

Now consider Student B, who realizes the exam is a week away and believes that she has attended each lab and therefore must at least have sufficient knowledge to perform adequately on the test, unaware of specific gaps in her knowledge. When she begins to study, she decides to re-read all of her notes (an ineffective study strategy; Dunlosky et al., 2013) as many times as she can prior to the exam in hopes that the behavior will provide the knowledge necessary to succeed. After the exam, results show that Student A succeeded on the exam and Student B did not. While Student B generated a study plan, it was not based on accurate metacognitive thoughts (i.e., Student A's accurate judgments of knowledge regarding certain mineral groups) and instead was based on naive theories of knowledge construction and deficient and/or inaccurate declarative and procedural metacognitive knowledge. As metacognitive thought was not driving study behaviors, other phases of the SRL cycle were not employed (i.e., no monitoring of progress toward study goals nor evaluation of results).

Why is understanding student self-regulation important?

As described above, some students may have greater metacognitive awareness and knowledge of SRL than others (Schraw et al., 2006). Regardless of whether they do so knowingly, all students engage in some aspect of self-regulation (Winne, 1995). When completing a task such as studying for an exam, most students go through multiple SRL cycles, until they decide that they have met their goals (Winne & Hadwin, 1998). During a semester in a single course, students will engage in multiple "units" of task-level SRL cycles and will receive instructor-provided feedback. In its most basic form, feedback is represented by a grade or score on a task, while more comprehensive responses may take the form of instructor comments, a grading rubric, or sample answers. Students may incorporate these external evaluations from these tasks into their self-reflections to improve their self-regulation strategies through adaptation (Winne & Hadwin, 1998). Unfortunately, students may bring faulty beliefs about learning strategies and tactics to the course (Karpicke et al., 2009) that can short-cut their attempts at effective self-regulation. Failure to correctly define the task initially, poor learning strategy choices, inaccurate reflections, and/or gaps in SRL cycles, can lead to poor student outcomes (Pintrich & Zusho, 2007; Figure 2).

Instructors can introduce activities into classes that scaffold the self-regulation skills students need to complete these SRL cycles and perform successfully. Knowledge of SRL and a delineated SRL model (Figure 2) can help researchers and instructors identify key measurable macro-level components (planning, action, reflection, regulation) in student learning. By targeting and measuring specific components of SRL (micro-level components), instructors can identify potential weak points for students in the SRL cycle and then select appropriate intervention strategies. Additionally, by illustrating the sequence of effective student strategies in an SRL cycle format, students and instructors can examine a more holistic picture of individual student learning processes. The cycle format allows students and instructors to get a better idea of why or how learning is or is not occurring. Instructors can use the SRL model (Figure 2) as an academic counseling tool when working with struggling students. Researchers can use the SRL model to frame their research, design interventions, or inform measurement of SRL in geoscience settings. By providing a concrete visual for the abstract conceptual model of the SRL process, students can have an opportunity to increase their metacognitive awareness and knowledge of their learning processes. By raising student awareness, instructors can help students better understand and monitor their own learning processes. Geoscience education research framed within SRL can seek to achieve these benefits.

SRL in collaborative learning environments

While SRL refers to the cycling of cognitive and metacognitive processes during an individual's interaction with a learning task, recently researchers have begun to investigate how SRL behaviors are utilized and constructed within group settings (Järvelä & Hadwin, 2013). Within undergraduate STEM education settings there has been an increased focus on collaborative work in the classroom via active learning strategies that have been shown to positively influence student variables (Freeman et al., 2014 for a review). As a result, seeking to understand how group members interact during a group task has particular importance. Considering that learning does not just occur individually in these settings, researchers have viewed group interactions via a social-constructivist perspective on learning (Järvelä & Hadwin, 2013; Winne et al., 2013) during which students collaborate and work together to construct SRL behaviors as a group entity (e.g., planning, monitoring of progress, evaluation of results) rather than solely as individuals.

Based on the Winne and Hadwin (1998) model of SRL, Järvelä and Hadwin (2013) expanded consideration of SRL into how group members interact during a group task. While effective SRL in a solo environment relies solely upon an individual's cognitive and metacognitive skills, group situations present opportunities for group members to contribute different behaviors related to the SRL cycle. Regulation in this context is theorized as a continuum from the completely solo or individual to the completely collaboratively constructed behaviors (Järvelä & Hadwin, 2013). Along this continuum are three distinct types of regulation: 1) individual SRL where all regulatory behaviors occur within the individual; 2) co-regulation of learning (Co-RL) where peers may temporarily support one another's SRL behaviors via feedback or confirmation of SRL strategy use; and 3) socially-shared regulation of learning (SSRL) that occurs when regulatory activities are evenly-distributed and constructed amongst members within the group (Järvelä & Hadwin, 2013; Panadero & Järvelä, 2015 for a review).

Though still in its relative infancy, increased instances of SSRL within groups have been correlated to increased group criterion performance (i.e., higher grades; e.g., Janssen et al., 2012; Volet et al., 2009) and lower perceptions of task difficulty which can facilitate more effective group behavior (e.g., Hurme et al., 2009), in addition to positive affective responses (e.g., increased enjoyment; Panadero & Järvelä, 2015). However, both the original purveyors of the construct and subsequent researchers reviewing recent work have suggested that additional work needs to be done to further constrain the construct and its potential benefits for students (Panadero & Järvelä, 2015).

One may now pose the question, "what can I do as an educator to foster metacognitive abilities to better inform the SRL behaviors of my students?" One approach employed by instructors as they begin to provide support for student learning behaviors is to pose reflection questions to students to prompt them to evaluate their progress on particular concepts, learning goals, questions, etc. during class (e.g., minute papers; McConnell et al., 2017). While an important first step, work in educational psychology has demonstrated that metacognitive and SRL behaviors can be fostered via explicit and direct in-class training and feedback (e.g., Callender et al., 2016; Nietfeld et al., 2006) and that this training should reflect the phases of SRL being promoted (Dignath & Büttner, 2008). Self-reflection is important, but is only one phase of the SRL cycle and if instructors are looking to promote SRL behaviors in their students, the activities and prompting being employed should go further than simple metacognitive prompts (e.g., "what is the most important thing you learned today?"). Further suggestions for fostering SRL behaviors are outlined below in the "Discussion and Recommendations" section.

Investigating SRL in DBER contexts

While SRL has been investigated broadly within the educational psychology community, investigation into SRL in discipline-based education research (DBER) settings is still emergent (NRC, 2012). While many of the cognitive and metacognitive skills that inform SRL have been demonstrated to be domain general (Schraw, 1998), other sources suggest that there is some discipline-specific variability in the application of SRL behaviors in different contexts (e.g., Schraw, Crippen, & Hartley, 2006). Toward this end, there have been several recent examples of studies investigating SRL in specific STEM-related settings. To synthesize the findings of these efforts for this review, we will discuss them organized by their essential design elements. First we will discuss studies that attempted to characterize college science students' SRL behaviors ("Measuring SRL without intervention") with or without correlating with other variables like performance. Then we will discuss studies that went a step further to attempt to foster SRL behaviors via an experimental intervention ("Measuring SRL with intervention"). Finally, we will discuss studies that not only measured SRL and attempted to foster SRL behaviors via an intervention, but also examined the relationship between measured SRL behaviors and students' grades/performance.

Measuring SRL without intervention

Often, the first step toward understanding a phenomenon is to simply attempt to characterize it in a particular context—in this case, in undergraduate science education settings, using real students enrolled in real courses (as opposed to compensated volunteers in lab settings, etc.). In the early 2000s, the originators of the Motivated Strategies for Learning Questionnaire (MSLQ; Pintrich & De Groot, 1990) partnered with faculty in chemistry at the University of Michigan to conduct an early investigation into discipline-specific SRL in two large enrollment (200+) chemistry courses (Zusho et al., 2003). Using the MSLQ to measure motivation and learning strategies, they found that while student motivation surrounding the course decreased as the semester progressed, their self-reported level of self-regulatory strategies increased over time (Zusho et al., 2003).

More recently, Lynch and Trujillo (2011) employed the MSLQ to investigate the conceptions of students toward the end of an organic chemistry course. They reported pronounced gender differences, with males reporting higher levels of SRL-related variables such as task value (Lynch & Trujillo, 2011). Overall and across genders, the authors noted correlations between the self-reported levels of SRL variables and performance, with higher reported levels of MSLQ subscales such as intrinsic motivation and task value being correlated with higher academic performance in the course (Lynch & Trujillo, 2011). Again, while important, these studies only attempted to correlate self-reported MSLQ scale variables across students and did not attempt to elicit change in the participants being studied. In biology, Sletten used the MSLQ to investigate introductory biology students' self-reported SRL strategy use in one large enrollment (75+) flipped biology course (Sletten, 2017). Results suggested that students' perceptions of the flipped classroom positively predicted their self-reported strategy use, but that SRL (as measured by the MSLQ) did not predict academic performance (Sletten, 2017).

In geoscience, as part of the GARNET project, Lukes (2012) used a grounded theory approach informed by student interview data, artifact analysis, and benchmarking, to characterize student choices about learning and influences on their learning, as well as participant MSLQ data, Geoscience Concept Inventory data, and academic data to explore the relationship between SRL and performance. The emergent model from the student data ($n = 63$; 26 from two community colleges and 37 from two research-intensive universities) converged with existing SRL models of learning, but provided additional characterizations of the differences in SRL processes of high and low performing students. This work suggested that there is a disconnect between course design, pedagogy, and student strategy use (relationship A to C in Figure 1) and that there were differences between community college and research intensive student populations in terms of timing of learning strategy acquisition and monitoring of learning (metacognitive skills relevant to SRL).

Lukes and McConnell (2013, 2014a, 2014b) also analyzed a portion of the interview data ($n = 42$) through a motivation and emotion theoretical framework, characterizing a strong relationship between motivation and emotion in SRL decision-making (relationship B to C in Figure 1). Lukes and McConnell (2014a) utilized student interviews to characterize the sources of students' motivation to study for geology exams. Interview results revealed that while all students harbored a performance goal orientation (i.e., all were motivated by their course grade), higher performing students had higher levels of mastery goal orientations (i.e., they were motivated to master the content in addition to getting a good grade). Additionally, these mastery goal orientations were theoretically linked to more effective use of SRL strategies (Lukes & McConnell, 2014a, 2014b).

In a physics context, a large portion of introductory physics courses at the college level leverage problem sets to guide student learning (e.g., Adams & Wieman, 2015). Mota et al. (2019) added reflection exercises to the end of such problem set homework assignments (e.g., "list assistance you sought while working on this problem set"; Mota et al., 2019). Additional learning strategy activities suggested by these reflective prompts included students color coding their responses for areas where they struggled and asking them to summarize the information they learned from the assignment (Mota et al., 2019). This study found that the number of students' comments coded as metacognitive increased as the semester progressed, specifically comments related to knowledge of cognition (i.e., comments coded as declarative, procedural, and conditional knowledge; Mota et al., 2019), suggesting that the underlying processes of SRL were strengthened.

As a whole, these studies seek to characterize and measure SRL behaviors through a confirmatory approach in course settings. Studies that rely solely on confirmatory self-report instruments such as the MSLQ are limited by the narrow SRL content of survey instruments and their underlying assumptions about SRL. The MSLQ contains a limited number of statements about very specific SRL subcomponents and there has been debate about the validity of the instrument to measure the constructs it purports as a result (e.g., Hilpert et al., 2013; Rovers et al., 2019). While valuable, these descriptive studies only serve as baselines in our understanding of SRL in these settings.

Measuring SRL behaviors with intervention

If the ultimate goal is increased student learning in these environments and learning is connected to effective SRL practices, the logical next step is to attempt to foster effective SRL behaviors in students who are not exhibiting these behaviors through instructor/course activity intervention. These attempts have been primarily conducted in relation to the common student experience of the course exam. Many researchers working in undergraduate STEM settings have asked students to reflect on their exam preparation behaviors pre- or post-exam to gain insight into their SRL strategy use and other behaviors. Often called "exam wrappers," these are assignments that have students considering (for example) recent exam results, the study strategies the students used to prepare for the recent exam, and how they plan to alter their study habits for subsequent exams (e.g., regulation; Lovett, 2013). Within DBER settings, studies implementing versions of these instruments have primarily taken place in biology settings (e.g., Metzger et al., 2018; Sabel et al., 2017; Smith et al., 2019; Stanton et al., 2015). There have been a number of conference presentations related to the use of exam wrappers in geology courses to support student study behaviors (e.g., Marton, 2015; Nunez et al., 2015; Perkins & Wirth, 2011; Wirth & Perkins, 2011). Results generally converge on two common themes: 1) variability in students' ability to identify effective SRL strategies to use; and 2) variability in the level of which they follow through with the effective strategies they may have identified. For example, Sebesta and Speth (2017), found that students largely failed to follow through with planned study strategy changes reported in the exam wrappers for two sequential exams (Sebesta & Speth, 2017). Contrastingly, Smith et al. (2019) found the opposite was the case, with a majority of students self-reporting planned and executed changes in study strategies that led increased exam performance from one exam to the next (Smith et al., 2019). Specifically for geoscience, Nunez et al. (2015) reported that students were mainly overconfident in their learning and most commonly reported using the learning strategy of rereading notes (a less effective learning strategy; Dunlosky et al., 2013).

Stanton et al. (2015) employed "metacognitive assignments" following each of the two course exams in a large-enrollment (250+) biology course. The first was given after the first course exam for students to monitor and evaluate their study behaviors to prepare for the exam and to make a study plan for the next exam (Stanton et al., 2015). The second, given after the second exam, asked students to reflect on the extent of which they followed through with the plans they outlined in the first assignment (Stanton et al., 2015). Approximately half of the students reported SRL behaviors (e.g., planning future learning strategy use, monitoring effectiveness of learning strategy use) during the assignments. While almost all of the students suggested that they would change their study strategies for future exams, many did not identify learning strategies shown to be effective (see Dunlosky et al., 2013 for a review of effective learning strategies), nor report following through with their altered study plans in subsequent assignments (Stanton et al., 2015). While each post-exam instrument and/or procedure in these "exam wrapper studies" had their idiosyncratic differences, they all generally converged upon practices of comparing expected and actual exam outcomes along with explicit communication of study strategies and planned alterations to a study plan for future exams with the general goal of increasing performance.

In addition to the practice of including exam wrappers to support increased awareness of their SRL behaviors after a course exam, some have approached fostering SRL via explicit training programs. Training models generally consist of providing students specific study strategies and feedback on the efficacy of these strategies throughout the training program. For example, an experimental study by Dörrenbächer and Perels (2016) sorted students from diverse fields of study (including natural sciences) into groups that; (a) received an 8-week SRL training program focusing on strategies and their effective use; (b) completed a learning diary cataloging their study strategies; (c) both, or; (d) neither. While the control group unsurprisingly saw no change in SRL outcomes, the learning diary group also demonstrated no significant improvement. While the training group saw improvements in students' self-reported SRL, the group that completed both the training and the learning diaries reported the highest gains in SRL variables (e.g., self-monitoring; Dörrenbächer & Perels, 2016). This suggests that while more reflection-based strategies may not be enough to impact students' SRL behaviors, explicit training in effective learning strategy use, particularly in combination with reflection-based strategies, more effectively supports student SRL skill growth. Although these training approaches have been widely employed in non-discipline-specific work in education psychology (e.g., Bellhäuser et al., 2016; Ferreira et al., 2015; Nietfeld et al., 2006), similar targeted training interventions in college STEM settings have yet to see such a diversity in application.

Other studies attempted to utilize a more-detailed measurement strategy toward investigating student SRL behaviors. Throughout a semester of organic chemistry, Lopez et al. (2013) gave students a number of tools (study diaries, problem sets, and concept maps) to help them navigate the semester and then collected/analyzed those tools to measure students' authentic SRL behaviors throughout the course (Lopez et al., 2013). By collecting completed tools, they were able to analyze them to determine students' study strategies and behaviors. They found that students were underusing higher quality strategies (e.g., metacognitive reflection and peer learning) and over-utilizing lower quality ones (e.g., reviewing the text; Lopez et al., 2013). While expanding the types of data collected beyond a self-report Likert-style survey, to include direct evidence of behavior through artifact analysis, they were able to gather a more-nuanced, and potentially more valid, understanding of students' SRL behaviors.

Finally, the construct of SSRL has been investigated within an online introductory geology course via the use of Google Hangouts. Spencer et al. (2018) embedded regulatory prompts into group activities facilitated by synchronous online chatting. Results suggested that prompting alone exerted enough of an influence on the interactions between group members to generate more examples of co-regulation (co-RL), but was not enough of an influence to generate more complex episodes of socially-shared regulation (SSRL; Spencer et al., 2018).

SRL interventions and correlations with performance

Other researchers have implemented SRL related interventions with the additional goal, and thus prediction, of increasing student performance in science courses. Pape-Lindstrom et al. (2018) reported the results of a multi-semester study at a two-year community college (2YC) implementing reading quizzes into an undergraduate biology course. The multiple-choice quizzes on reading assignments were presented as tools to increase course structure and support students' SRL by providing feedback during self-study that students would theoretically use to regulate their learning, therefore better preparing them for future active learning lecture sessions (Pape-Lindstrom et al., 2018). Results revealed that the semesters with the reading quizzes (controlling for other student variables such as non-biology GPA) saw a significant increase in exam performance (~5% increase; Pape-Lindstrom et al., 2018). Though there were increases in performance, this study did not measure SRL variables directly, however, given the increase in performance and importance of 2YC environments in geoscience, this approach, if explicitly connected to SRL components, could be used by the GER community as a tool to identify SRL behaviors.

Other studies, in contrast, directly measured SRL strategy use in undergraduate biology settings. Sebesta and Speth (2017) developed their own survey instrument based on an existing interview protocol designed to evaluate student's SRL strategy use (Zimmerman, 1989; Zimmerman & Martinez-Pons, 1986) and evaluated the strategies used by students in their flipped biology course twice during the semester (after the first and second exams). They evaluated both the cumulative reported use of each specific strategy (e.g., seeking instructor assistance, reviewing notes), compared these to the students' grades, and calculated how these patterns changed between each survey. Results revealed significant differences based on exam performance, with both high performing students and those who improved from exam to exam reporting using more strategies than lower-performing students (Sebesta & Speth, 2017). Additionally, lower-performing students reported a lower adherence to following through with the strategies they planned on implementing (Sebesta & Speth, 2017). These studies suggest that direct instructional interventions that are designed to foster student SRL strategy use have the potential to improve learning outcomes.

Discussion and recommendations

Goal #1: Providing a theoretical framework for SRL to situate future investigations

SRL models provide a way to explain observed differences in student performance, and therefore learning (by proxy). Exploring SRL conceptual frameworks in geoscience contexts is one clear pathway for the GER community to effectively work toward a broader goal of improving student learning and performance in geoscience. While Lukes (2012) and Lukes and McConnell (2014a), have reported some mapping of such SRL models in a geoscience discipline context, in general, there is little data about whether these models work in college-level science discipline contexts. Mapping out the nexus between conceptual SRL frameworks and actual learning experiences is a key part to advancing our understanding of SRL broadly, as well as student learning and success in geoscience specifically. It is important to explore these SRL frameworks in practice with real students situated in formal and informal learning experiences (e.g., courses, lab/field/research projects, museum exhibits, science center programs, clubs, citizen science projects) rather than experimental settings because understanding the realities of student experience is what provides the link to choices in pedagogical design and instructor practice. In other words, translating SRL research into geoscience teaching and learning practice. As discussed above, targeted interventions have been shown to increase both the frequency and efficacy of SRL-related strategy use in students in other college science contexts (e.g., Dörrenbächer & Perels, 2016; Sebesta & Speth, 2017), but these need to be tested and refined for geoscience-specific contexts. Tools and pedagogical approaches can therefore be developed and refined to better support students for success in geoscience. Such success has implications for recruitment and retention.

Aside from promoting effective SRL behaviors in the geoscience classroom, it is important for researchers interested in this space to consider the specific features of the geosciences and how research into SRL can help augment geoscience instruction. Specific attributes of geoscience education (e.g., field work, spatial abilities, abstraction) pose unique challenges to effective learning. Targeted research studies investigating: a) how students approach common geoscientific tasks via specific SRL strategies and; b) what kind of interventions can help foster effective SRL strategy-use to enhance learning are presently sparse (Lukes, 2012) and warrant future work.

One particularly salient opportunity for geoscience education researchers is in the developing realm of SSRL. Given the importance placed upon effective group work in both educational and professional geoscience settings, geoscience education researchers are particularly well-positioned to further the understanding of socially-constructed regulatory behaviors not only within our discipline, but in educational psychology more broadly. What kind of SSRL strategies are employed during effective field work? … collaborative mapping activities during field camp? … in active learning environments? Though some preliminary work has been conducted (Spencer et al., 2018), these are questions that can be investigated to help remedy this gap in the literature.

Goal #2: Methods of studying and supporting effective SRL practices in learners

We need to understand what SRL strategies learners are currently using in geoscience learning experiences so that we can ultimately focus on developing targeted support for effective SRL strategy use. We see from the Educational Psychology Community and other STEM DBER Communities that a variety of self-report tools (survey instruments, reflection prompts/diaries, interviews, think aloud protocols) exist for use in documenting and measuring the SRL practices of learners. Less explored are tools for artifact analysis, SRL-specific pedagogical observation, and participant behavior observation technologies (trace data collection and analysis from learning management systems, learning analytics from adaptive tutoring tools, eye tracking, digital badges and biometric monitors). With the prevalence of online learning experiences and emerging technologies related to virtual reality, augmented reality, and mixed reality, these tools are increasingly important to incorporate into our understanding of SRL.

In terms of broader methodological approaches, SRL research is largely emergent in the GER community and currently based on more qualitative methods. Referencing the Strength of Evidence Pyramid outlined in St. John and McNeal (2017) from an educational psychology lens, the research conducted on SRL spans all levels and is robust in volume. Narrowing focus to college level geoscience applications, this abundance becomes a paucity. The majority of extant SRL research conducted in geoscience contexts are either cases of practitioner wisdom or preliminary data presentations (e.g., conference presentations; Wirth & Perkins, 2011; Perkins & Wirth, 2011; Marton, 2015; Nunez et al., 2015) or in some isolated cases published case studies (e.g., Spencer et al., 2018). The only example of a cohort study was that of Lukes and McConnell (2014b), though the analysis therein was primarily associated with sources of motivation and goal orientations (i.e., SRL was only considered as a potential influence on results). Future work should seek to move the community-wide understanding of SRL in geoscience up the strength of evidence pyramid via increased case and cohort studies investigating SRL variables.

Goal #3: Summary of possible future directions for SRL research in geoscience

The future directions for SRL research in geoscience contexts can be summarized in three broad areas: lines of inquiry, corresponding methods, and strategies for translating research into practice. In terms of lines of inquiry, several fundamental framework questions emerge from this review.

First, *do SRL models explain differences in learning and performance in geoscience learning contexts?* There are several priority research questions for the GER community. Namely, how are students regulating/not regulating their learning in geoscience contexts both individually and in group settings? What micro-level processes do they use? Do processes vary with specific types of learning activities or attributes of geoscience (e.g., field work, spatial abilities, abstraction)? What influences their underlying beliefs about how learning works and their corresponding SRL choices in geoscience contexts?

Second, *what methods can we employ to best document SRL in geoscience learning contexts?* There has already been initial work in GER around the use of self-report SRL data in the form of exam wrappers (e.g., Marton, 2015), strategy-use surveys (Nunez et al., 2015), and student interviews that include think aloud protocols (Lukes, 2012; Lukes and McConnell, 2014a, 2014b). However, the relationship between self-reported SRL practice and actual practice remain unknown in these studies, which is consistent with the criticism of SRL studies in general that self-report SRL data is less trustworthy data in capturing students' SRL subprocesses and applications (Rovers et al., 2019). There is a clear need in SRL studies and therefore the GER community engaging in such studies to attempt to triangulate self-report data. with trace evidence (artifact analysis, learning management/learning analytics metadata, direct observation). Future SRL studies in GER should therefore consider such limitations and explore the use of additional methods to validate findings through triangulation. The GER community is encouraged to test existing methods and tools for documenting SRL from other fields such as educational psychology, as well as develop and validate new ones. Think-aloud protocols or written reflection artifacts in which participants describe their thought process while engaging in a task or when reviewing video documentation of doing a task allow researchers to identify mismatches in participant belief and SRL action (Ericsson, 2006). Online learning activities provide trace data (e.g., resource access, learning tool use frequency, etc.) that could also be used to triangulate self-report data from participants (e.g., Jones & McConnell, 2019). Other sources of data could include artifact analysis, learning analytics metadata, and direct observation.

Finally, we may ask *how can these findings be translated into practice? What interventions can be employed to increase effective SRL skills and strategy/tactic use? And, can SRL support interventions be used to increase learning/performance?* Some preliminary work has been reported through conference presentations and workshop discussions, but there is a clear gap in the published peer-reviewed record. Providing peer reviewed evidence of intervention value is critical to the successful translation of SRL research into practice to improve student learning in geoscience. Once (un)successful intervention studies are documented, then practitioners can use the reported findings to inform their learning support task selections and teaching practices, to ultimately benefit students. Given the importance of metacognitive skills and knowledge in effective SRL processes, priority should be given to testing interventions that aim to increase learner SRL-related skills such as metacognitive awareness and knowledge; control and learning strategy/tactic use; learning judgment accuracy; and task analysis. Priority should also be given to interventions that seek to support student SRL in the learning tasks or situations common to geoscience contexts such as field and lab settings; visualization and/or spatial thinking activities; abstraction activities; and collaborative group learning situations. How can instructors best design and scaffold learning support tasks in these contexts to support SRL, SSRL, and Co-SRL?

Conclusion

Though prior work has laid a solid theoretical foundation for the investigation of students' SRL behaviors in college geoscience courses, only the first tentative steps toward identifying best practices in supporting student SRL strategy use have been undertaken. Future work should seek to identify several important, step-wise, phenomena that influence student SRL behavior. For example, we should seek to determine the suite of metacognitive skills undergraduate students bring to an introductory geoscience course due to the importance of metacognition in driving effective SRL behaviors. Additional work could then solicit student rationale for the selection of various study strategies. Finally, we could investigate what kind of instructor-led interventions could potentially "level the playing field" by promoting students SRL abilities for not only general success in the course but for increased opportunity for equity in instruction. Though these pursuits could be approached via traditional (e.g., survey-based) data collection activities, with the rise and proliferation of new educational technology we encourage geoscience education researchers to "think outside the survey" and seek additional data sources that capture a more-authentic record of behavior (e.g., online trace data, etc.). Given the potential benefits for both geoscience students and geoscience education research, we encourage geoscience educators and geoscience education researchers alike to support SRL interventions to potentially improve student learning.

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