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Preservice science and mathematics teachers' acculturation into communities of practice: A call for undergraduate research in science and mathematics teacher preparation

Cover Page Footnote

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Preservice science and mathematics teachers' acculturation into communities of practice: A call for incorporation of undergraduate research into teacher preparation

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Abstract

Current mathematics and science standards, namely the Common Core State Standards of Mathematics (CCSSM) and the Next Generation Science Standards (NGSS), emphasize engaging students in mathematical and scientific practices. This review article is driven by the question: How can we expect science and mathematics teachers to appropriately engage students in the practices of the scientific and mathematical disciplines, when most teachers themselves lack experience practicing as scientists and mathematicians? To address this question, we review the literature on teachers' understanding of their discipline's practices, disciplinary practices as means to engage in inquiry, and how preservice teacher engagement in undergraduate research experiences may contribute to fostering desirable understandings of their disciplines' practices. We further posit that the communities of practice framework allows teacher educators to conceptualize how undergraduate research can foster understandings of inquiry through engagement in science and mathematical practices, thereby enabling science and mathematics teachers to construct communities of scientific and mathematical practice, respectively, in their own classrooms. We conclude with a call to both provide undergraduate research experiences to preservice science and mathematics teachers as well as an exploration of research that is needed to fully conceptualize the benefits of undergraduate research for preservice science and mathematics teachers.

Keywords: preservice teachers, undergraduate research, communities of practice, inquiry, science and engineering practices (SEPs), standards of mathematical practice

With widespread adoption of the Common Core State Standards of Mathematics (CCSSM) and the Next Generation Science Standards (NGSS), curricular goals within the STEM fields have shifted. These standards emphasize understanding scientific and mathematics concepts, in addition to engagement in science and mathematics as processes of inquiry (NGSS Lead States, 2013; National Governors Association Center for Best Practices [NGA] & Council for Chief State Officers [CCSO], 2010). However, teachers' lack of experience with and knowledge about these practices limit how well they are taught in classrooms (Ricketts, 2014).

The practices described in the standards portray scientists' and mathematicians' actions and behaviors as they engage in inquiry within their disciplines; inquiry builds skills, including the ability to analyze large data sets, collaborate with peers, and design experiments (Marshall, 2013). To prepare their students for the future, teachers need to allow students to construct their own understandings, work collaboratively, and engage in inquiry to identify solutions to real-world, complex problems (Marshall, 2013). To enable inquiry learning, the new mathematics and science standards highlight the importance of problem-based, interdisciplinary lessons that engage students in authentic problem-solving (Mayes & Koballa, 2012).

Inquiry learning persists throughout both mathematics and science classroom content and learning goals (Blanchard et al., 2010; Laursen et al., 2016; O'Brien et al., 2015; Wilson et al., 2010). Inquiry learning can reduce the achievement gap between high- and low-achieving students, increase interest in the content, and deepen understanding (Laursen et al., 2016). Inquiry also creates positive learning opportunities for students (Blanchard et al., 2010; Laursen et al., 2016; Wilson et al., 2010). For example, inquiry learning can increase a student's ability to understand core ideas, learn in more dynamic ways, and collaborate with fellow students (Marshall, 2013).

Inquiry learning is at the heart of STEM education, so effective teachers need to experience how inquiry enables learning. Undergraduate research experiences (UREs) likely provide preservice teachers with opportunities to engage in the inquiry of their discipline, so they build their knowledge of inquiry firsthand. UREs have improved student interest in science and helped students build robust understanding of scientific inquiry (Hunter et al., 2007). UREs provide opportunities for students from all backgrounds to engage in research practices and collaboration (National Academies of Sciences, Engineering, and Medicine [NASEM], 2017), as well as a likely avenue to build skills and motivate preservice teachers to teach inquiry by incorporating the practices of their respective disciplines into their pedagogy. There has been limited research on preservice teacher understanding and intention to integrate the practices of their disciplines into future teaching. Also, to our knowledge, no research has investigated preservice teachers' engagement in the practices of their disciplines outlined in their standards.

Since the development and adoption of the CCSSM and NGSS, mathematics and science teachers are expected to teach inquiry through standards of mathematical practice (SfMP) and scientific and engineering practices (SEPs), respectively. In this article, we collectively refer to these practices, as defined by their respective standards, as disciplinary practices. As mentioned above, potential benefits of UREs include increased interest, understanding, and knowledge within scientific and mathematics disciplines (NASEM, 2017), but few have considered how preservice science and mathematics teachers develop understanding of their discipline's practices, particularly during research experiences. Currently, a URE is not a standard component of teacher education programs, but UREs could be an effective way to develop knowledge of disciplinary practices, which they will be expected to engage students in as teachers. It is uncertain how UREs embed the foundational skills of how to engage in practices within preservice teachers and how this extends into their teaching. While some studies have considered mentoring relationships within UREs and student experiences, very few studies have considered the culture of UREs and understanding of disciplinary practices, let alone how the unique characteristics of research settings may impact student outcomes (NASEM, 2017). In addition, few studies have considered the long-term understanding and teaching integration of disciplinary practices into classrooms. The purpose of this article is to explore the literature on scientific and mathematics teachers' understandings of the practices of their respective disciplines, how disciplinary practices compel

engagement in inquiry, the potential influence of UREs on preservice teachers' understanding of their discipline's practices, and UREs' potential usefulness in preparing science and mathematics teachers. We conclude with a call to expand current knowledge of factors that foster science and mathematics teachers' understanding of the practices of their disciplines, which we claim should include preservice STEM teachers' engagement in UREs as part of their preservice STEM teacher preparation.

Practices of the Scientific and Mathematical Disciplines

The NGSS encompasses three overlapping components of scientific knowledge: disciplinary core ideas, crosscutting concepts, and scientific practices (NGSS Lead States, 2013). Crosscutting concepts are ideas that bridge the scientific disciplines and between science and engineering (e.g., structure and function); disciplinary core ideas are specific ideas unique to each scientific discipline; and scientific and engineering practices are the behaviors used to investigate natural phenomena and build theories (NGSS Lead States, 2013). Each standard within the NGSS combines these three elements to define proficient science understanding. Each dimension is equally important for student understanding of science; however, research experiences will likely involve students in the practices outlined by the NGSS. These practices are (1) asking questions and defining problems, (2) developing and using models, (3) planning and carrying out investigations, (4) analyzing and interpreting data, (5) using mathematics and computational thinking, (6) constructing explanations and designing solutions, (7) engaging in argument from evidence, and (8) obtaining, evaluating, and communicating information (National Research Council (NRC), 2012) See Table 1.

The CCSSM were developed in order to create a deeper understanding of mathematics concepts and skills (NGA & CCSSO, 2010). These standards shift mathematics standards to focus on fewer topics, highlight connections between mathematics concepts across grades, and provide rigorous conceptual understanding, procedural skills, and application (NGA & CCSSO, 2010). In addition, these standards include mathematics practices. The Standards for Mathematical Practice (SfMP) describe mathematics skills required for mathematic proficiency (NGA & CCSSO, 2010). SfMP use both procedural and content-based mathematics concepts that enable real-world problems to be solved (NGA & CCSSO, 2010). The SfMP include 1) making sense of problems and persevering in solving them, 2) reasoning abstractly and quantitatively, 3) constructing viable arguments and critique the reasoning of others, 4) modeling with mathematics, 5) using appropriate tools strategically, 6) attending to precision, 7) looking for and making use of structure, 8) looking for and expressing regularity in repeated reasoning (NGA & CCSSO, 2010) See Table 2.

Both SEPs and SfMP are unique to their respective disciplines, but there are areas of overlap. For example, both SEPs and SfMP include developing models that may show the relationships between variables and the real-world (Stage et al., 2013). Also, SEPs and SfMP include justifying claims and evaluating arguments based upon evidence and logic (Mayes & Koballa, 2012). Other potential areas of overlap include constructing arguments, computational thinking, and asking questions and defining problems (Davis et al., 2014; Mayes & Koballa, 2012; Stage et al., 2013). These disciplinary practices are the means through which scientists and mathematicians engage in the inquiry of their discipline.

Table 1
 NGSS Scientific and engineering practices and descriptions

Practice	Description
1. Asking questions and defining problems	In science, ask questions to formulate, refine, and evaluate empirically testable questions using models and simulations. In engineering, identify problems and develop designs for useful novel technology.
2. Develop and use models.	In science, use, synthesize, and develop models to predict and explain relationships among variables between systems and their components in the natural world. In engineering, models are utilized to analyze and evaluate technologies.
3. Planning and carrying out investigations.	In science, investigations provide evidence for and test conceptual mathematical, physical, and empirical models. In engineering, investigations are often iterative evaluations of prototypes.
4. Analyzing and interpreting data.	In science, learn more detailed statistical analysis, the comparison of data sets for consistency, and the use of models to generate and analyze data of the natural world. In engineering, analysis also includes diverse criteria including scientific and stakeholder requirements.
5. Using mathematics and computational thinking.	Use algebraic thinking and analysis, a range of linear and nonlinear functions including trigonometric functions, exponentials, and logarithms, and computational tools for statistical analysis to analyze, represent and model data. Simple computational simulations are created and used based on mathematical models of basic assumptions. Engineering also involves designing concrete items based on real and simulated data.
6. Constructing explanations and design solutions.	Explanations are supported by multiple and independent student-generated sources of evidence consistent with scientific ideas, principles, and theories. In science, focused on a single “best explanation” for natural phenomena. In engineering, designing solutions involves identifying the “best design solution” based on problem and consideration of tradeoffs (e.g., cost to manufacturer).
7. Engaging in argument from evidence.	Use appropriate and sufficient evidence and scientific reasoning to defend and critique claims and explanations about the natural and designed worlds. Arguments may also come from current scientific or historical episodes in science. In engineering, evidence is utilized to satisfy client needs.
8. Obtaining, evaluating, and communicating information.	Obtain information from multiple sources, evaluate the claims, credibility, and relevance of sources for scientific or engineering enterprise, and communicate findings to the larger scientific community (both verbally and in writing). In engineering, novel ideas are considered proprietary legally and the information is guarded.

Note: Modified from NGSS Lead States (2013) and Cunningham & Carlson (2014), Schwarz et al. (2017).

Table 2
CCSSM standards for mathematical practice and descriptions

Standard	Description
1. Make sense of problems and persevere in solving them.	Being able to analyze givens, constraints, relationships, and goals through self-monitoring, explanations, and logic.
2. Reason abstractly and quantitatively.	Ability to decontextualize and contextualize during problem solving. Creating representation of the problem, considering the units involved, and attending to the meaning of quantities.
3. Construct viable arguments and critique the reasoning of others.	Understand and use assumptions, definitions, and results in constructing arguments. Make conjectures and build logical progression of statements. Justify conclusions, communicate findings, and respond to critiques.
4. Model with mathematics	Apply mathematics to solve problems in everyday life. Comfort in making approximations and assumptions to simplify complex scenarios.
5. Use appropriate tools strategically.	Consider all tools available to solve problems, including simple tools like paper and pencil and more complex tools like calculators and computer modeling software. Understand both the advantages and limits of tools as well as functions and solutions generated. Able to detect possible errors within tools.
6. Attend to precision.	Communicate precisely to others with clear definitions. Describing meanings of symbols, providing units, and label axis. Able to calculate accurately and efficiently.
7. Look for and make use of structure.	Discern a pattern or structure and note complicated things as being single objects or several components.
8. Look for and express regularity in repeated reasoning.	Notice when calculations are repeated and consider general methods and shortcuts.

Note: Modified from NGA & CCSSO (2010).

Inquiry-based Pedagogy and Disciplinary Practices

Inquiry-based pedagogies have been introduced within science and mathematics reform documents (Capps & Crawford, 2013). While there are many definitions of inquiry, three definitions are worth noting: 1) inquiry as content (e.g., the nature and epistemologies of the science and mathematics disciplines); 2) inquiry as action (e.g., engagement in disciplinary

practices); and 3) inquiry as pedagogy (e.g., utilizing guided or open inquiry instructional methods) (Capps & Crawford, 2013). This paper focuses primarily on the second aspect of inquiry. Preservice teachers should be able to deliver inquiry-based teaching that parallels the work of practicing scientists (Capps & Crawford, 2013) and mathematicians, so preservice teachers need to come to understand the inquiry practices of their discipline and be active members in the research process in order to be able to do so.

Inquiry-based pedagogy has been connected to many learning goals in both mathematics and science classrooms. Inquiry-based pedagogy enhances student levels of reasoning and argumentation, a key component of the disciplinary practices defined by the standards (Laursen et al., 2016; Wilson et al., 2010). In addition, students receiving inquiry-based pedagogy, which engages them in the disciplinary practices, are better able to persist in problem-solving (e.g., understanding of multiple solutions and pathways to solve problems), learn from the criticism of others, and experience increased interest in the content (Flores et al., 2017; O'Brien et al., 2015; Pudwell, 2017). These benefits extend beyond learning experiences. Inquiry-based pedagogy enables disciplinary practices; engaging in inquiry-based lessons enhances students' interest and provides an avenue to stronger understanding of the disciplinary practices.

Preservice Teacher Understanding of Disciplinary Practices

Science and mathematics practices are interwoven into the framework of the NGSS and CCSSM; therefore, an understanding of these disciplinary practices is essential for science and mathematics teachers to be effective. Disciplinary practices understanding has been explored to a limited degree within secondary preservice and in-service teachers, as elementary teachers are the primary focus of research on disciplinary practices understanding. We synthesize these findings, nonetheless, because they provide a basis for understanding how teachers conceptualize the practices.

Science practices. Developing and using models (SEP2), constructing explanations (SEP6), and engaging in argument from evidence (SEP7) were often absent from in-service and preservice teacher lesson planning and portfolios (Brownstein & Horvath, 2016; Merritt et al., 2018). Therefore, it is unsurprising that literature has primarily focused on interventions to improve preservice and in-service teachers' understanding and classroom implementation of argumentation (SEP7), explanation (SEP6), and modeling (SEP2).

Argumentation and explanation. Engaging in argument from evidence (SEP7) and constructing explanations (SEP6) are often conflated; preservice and in-service teachers are unable to separate the purposes of these practices (Aydeniz & Ozdilek, 2015; Osborne & Patterson, 2012; Ricketts, 2014). Constructing explanations develop cause and effect mechanisms for a phenomenon; in contrast, argumentation considers if the explanation is valid or compares competing ideas (Osborne & Patterson, 2012). While these two practices are intertwined, the level of entanglement is under debate in the science education community (Osborne & Patterson, 2011; Berland & McNeill, 2012; Osborne & Patterson, 2012). Nonetheless, more research has been devoted to preservice teachers' development of argumentation skills than has been devoted to their development of explanation construction skills.

Argumentation with evidence (SEP7) takes time and practice to develop (Driver et al., 2000; Zembal-Saul, 2009). Preservice teachers often fail to acknowledge the importance of considering alternative claims, a key element in scientific argumentation (Dalvi et al., 2020; Osborne &

Patterson, 2012; Zembal-Saul, 2009). In addition, argumentation classroom implementation is viewed as teacher-centered and, often, a formal classroom debate (Dalvi et al., 2020). However, interventions focusing on using evidence for arguments have enhanced participant knowledge of argumentation (Brownstein & Horvath, 2016). Incorporating evidence into explanations is a challenge for preservice teachers (Merritt et al., 2018), which is likely due to an inability to separate inference from evidence (Berland & Reiser, 2008).

Scientific modeling. Preservice and in-service teachers were able to describe models as characteristics of phenomena used to identify parts of a system; however, preservice teachers often fail to apply models as sense-making tools to help construct explanations for both the seen and unseen natural world (Carpenter et al., 2019; Dalvi et al., 2020; Louca & Zacharia, 2012; Ricketts 2014; Schwarz, 2009; Wang et al., 2014). Using models for predictions (Ricketts, 2014; Windschitl & Thompson, 2006) and to describe mechanisms and processes is usually not discussed (Louca & Zacharia, 2012; Windschitl & Thompson, 2006). Also, few preservice teachers acknowledge the iterative testing and revision of models based on data (Göhnur & Krell, 2020). Preservice and in-service teachers grappled with what “counts” as a model (Ricketts, 2014; Van Driel & Verloop, 1999). As such, preservice and in-service teachers describe models as hands-on materials for students to learn scientific facts (Dalvi et al., 2020; Ricketts, 2014; Windschitl & Thompson, 2006), or as a way to simplify systems to make them easier for students to understand (Schwarz, 2009). Preservice teachers are able to discuss specific elements of modeling aligned with NGSS; however, nonnormative conceptions are still expressed (Carpenter et al., 2019), and overall, knowledge of modeling is limited and inconsistent (Van Driel & Verloop, 1999).

Less-studied science practices. The specific practices of asking questions (SEP1), planning and carrying out investigations (SEP3), analyzing and interpreting data (SEP4), using mathematics and computational thinking (SEP5), and obtaining, evaluating, and communicating information (SEP8) have been studied less frequently than argumentation (SEP7), modeling (SEP2), and explanation (SEP6). However, research in elementary education preservice teachers has revealed non-normative understandings for each of these practices. Questioning (SEP1) is viewed as students and teachers posing questions; less attention is given to separating out empirical questions from other forms of questioning (Dalvi et al., 2020; Ricketts, 2014). Preservice elementary education teachers equate carrying out step-by-step labs with planning and carrying out investigations (SEP3); discussions of planning investigations and connecting these investigations with research goals and questions is rarely addressed (Dalvi et al., 2020). Also, planning and carrying out investigations is equated with experimentation; preservice teachers do not discuss other forms of investigations (e.g., observational studies) (Ricketts, 2014).

The practice of analyzing and interpreting data (SEP4) has been less common in preservice teacher edTPA portfolios (Brownstein & Horvath, 2016). Preservice teachers tend to conflate analysis and interpretation and are unable to connect organizing and finding patterns as analyzing data and making sense of the patterns as interpreting data (Brownstein & Horvath, 2016). This could be connected to preservice teachers’ lacking the ability to structure data (Bowen & Roth, 2005) or limited experience or understanding on how to implement data analysis and interpretation into teaching practice (Ricketts, 2014). Using mathematics and computational thinking (SEP5) has been equated with plugging numbers in formulas, performing statistical analysis, incorporating technology (e.g., computers, tablets, etc.) into classroom activities (Dalvi et al., 2020), and developing graphs and organizing data (Ricketts, 2014). Preservice teachers tend not to consider the deep thinking required to make sense of values and solve problems with mathematical tools

(Dalvi et al., 2020; Brownstein & Horvath, 2016; Wilkerson & Fenwick, 2017). Finally, the practice of obtain, evaluate and communicate (SEP8) seems to be the least informed practice for preservice teachers (Dalvi et al., 2020); preservice teachers saw this practice as a summary of the scientific method in which an individual obtains data from a scientific experiment, evaluates the results through analysis, and then communicates findings to others (Dalvi et al., 2020). We note that all of these practices are commonplace in undergraduate research experiences.

Preservice teachers display a continuum of understanding across each of these practices (Dalvi et al., 2020), encompassing normative and non-normative ideas as well as a failure to recognize elements of the practices. Non-normative ideas are attributed to unfamiliarity with the practice and its importance to scientific inquiry (Bowen & Roth, 2005; Ricketts, 2014; Windschitl & Thompson, 2006), lack of experience with practice (Bowen & Roth, 2005; Brownstein & Horvath, 2016; Windschitl & Thompson, 2006), and inability to make connections between practice and inquiry (Schwarz, 2009). In addition, for science preservice teachers, traditional college level courses tend not to allow for the development of inquiry knowledge (Windschitl, 2004). Capps and Crawford (2013) suggest an increased understanding of research processes would enhance the level of inquiry pedagogy within classrooms. Thus, it seems plausible that engagement of preservice teachers in UREs would serve to alleviate aspects of these challenges.

Standards of Mathematical Practice. The mathematics education community has considered mathematics preservice teachers and SfMP understanding. Professional development of in-service teachers revealed it was inadequate for experienced teachers to understand the differences and connections between each SfMP by only reading through standards (Bostic & Matney, 2014; Bleiler et al., 2015; Olson et al., 2014). Mathematics teachers have surface level understanding of precision (SfMP6) and do not consider attending to the precision of language (Cheng, 2017; Machmer-Wessels, 2015). Further, experienced mathematics teachers have diminished perseverance in problem-solving (SfMP1) (Bostic & Matney, 2014; Machmer-Wessels, 2015) and less than optimal abstract reasoning skills (SfMP2) (Davis & Osler, 2013). Also, modeling with mathematics (SfMP4) was often viewed as a teacher directly modeling how to complete a solution on the board so students could mimic their problem-solving behavior (Olson et al., 2014). Argumentation (SfMP3) was common in mathematics preservice teaching methods coursework; however, Max and Welder (2020) point out that argumentation should focus on exploring inaccurate reasoning of arguments to maximize efficacy. Finally, attending to structure (SfMP7) and repeated reasoning (SfMP8) were often conflated (Bleiler et al., 2015).

Most investigations of SfMP focus on the pedagogical implementation of SfMP instead of teacher understanding. Some studies highlight the variability of teacher views about SfMP practices of reasoning and utilizing proofs within pedagogy (Davis & Osler, 2013; Kotelawala, 2016; Machmer-Wessels, 2015). The SfMP are less clearly interwoven into the CCSSM than the SEPs are to the NGSS; the SfMP are often seen as separate standards of the CCSSM, causing challenges in teacher implementation (Machmer-Wessels, 2015). Teachers were excited about the SfMP and believed they were integrating the practices into their classrooms; however, this integration is often built upon a simplistic understanding of the SfMP (Machmer-Wessels, 2015) and are interpreted as teacher-centered instead of student-centered behaviors (Olson et al., 2014). Interventions have enhanced teacher understanding of SfMP (Cheng, 2017; Graybeal, 2013). Teacher collaboration, textbooks, professional development, and conferences may help teachers develop and integrate SfMP into their classrooms, but interventions have not been successful in enhancing teacher SfMP understanding (Machmer-Wessels, 2015). There is limited research about

the influences of SfMP teacher understanding and no known research on how UREs impact participant SfMP understanding.

Understanding of Inquiry-based Pedagogy

In addition to knowledge of disciplinary practices, teachers need to have a robust understanding of inquiry-based pedagogy in order to compel students' engagement in disciplinary practices (Osborne, 2014). Inquiry-based teaching leads to gains in student outcomes and understanding of both mathematics (Laursen, et al., 2016) and science (Stone, 2014). However, many teachers equate inquiry-based pedagogies with hands-on learning, instead of the actions and processes scientists use to complete their work or the disciplinary practices (Capps & Crawford, 2013; Osborne, 2014). Some teachers do not have experience with or an understanding of inquiry as action and thus do not see connections between inquiry and disciplinary practices (Capps & Crawford, 2013; Kang, et al., 2013; Marlow & Stevens, 1999). Many studies have highlighted the need for increased understanding of both scientific and mathematics practices, and some research has demonstrated that teachers at multiple levels gain better understanding of disciplinary practices after an intervention (Ricketts, 2014; Schwarz, 2009; Windschitl & Thompson, 2006). Interventions include activities such as detecting learning cues while reflecting upon video clips (Graybeal, 2013), an elementary scientific practices methods course (Ricketts, 2014), and an inquiry-based graduate course (Flores, et al., 2017). Other studies have suggested engaging in inquiry-based learning increases the likelihood of teaching through inquiry in the future (Capps & Crawford, 2013; Flores, et al., 2017). Finally, performing student-based investigations may build the skills and knowledge of authentic inquiry (Capps & Crawford, 2013) and these experiences may build familiarity with scientific and mathematics practices, which in turn may support teaching practices in the future (Graybeal, 2013).

Cultural Aspects of UREs

Culture is relevant to preservice STEM teachers' UREs. While there have been many definitions of culture connected to ethnographic studies of scientific spaces, including the relationships between people and objects within laboratory settings (Ayar et al., 2015) and social and individual aspects within science institutions (Godin & Gingras, 2000), we adopt Falk and Dierking's (2000) notion of culture as a collection of shared beliefs and customs. These may include: 1) customary ways of being, 2) codes or assumptions, 3) artifacts, 4) institutions, and 5) patterns of social relations (Ogbu, 1995). Mathematics and scientific working groups possess distinct structure, routines, and collaborations (Hagstrom, 1976), and these disciplinary differences are expressed through the disciplinary practices. These practices provide a shared set of customs within their respective disciplines about important abilities and the generation of knowledge. For example, scientific practices are customary ways of developing scientific knowledge. Epistemological understandings within science, like the nature of science, outline specific codes and assumptions within the scientific community (e.g., scientific theory). Also, each discipline has its own set of codes (common procedures), assumptions, and artifacts (e.g., equipment, thinking tools, methodological techniques) to accomplish the overarching goal of continuing to advance knowledge. The development of disciplinary knowledge varies based on the institutional goals (e.g., teaching versus research focus) and societal norms (e.g., grant-funding). Finally, each individual research setting has specific patterns of social relations that separate it from other spaces, even within the same institution. An individual interacting within a research space potentially interacts with all of these elements of culture, including disciplinary practices.

While scientific and societal culture is used in the broad sense, UREs occur within specific cultural units. Communities of practice (CoPs), a theoretical framework developed through observations of apprenticeships, are relationships among individuals that share activity and work together to improve their performance (Lave & Wenger, 1991). CoPs have a continuum of individuals (e.g., novice to expert, newcomer to old-timer) moving from the periphery to the center of the community (Lave & Wenger, 1991; Nistor et al., 2015; Wenger, 1998). In addition, CoPs require a domain or shared interest, a community in which members share information with each other, and a practice or shared experiences, stories, tools, and/or procedures (Wegner-Trayner & Wegner-Trayner, 2015). CoPs embed learning with collaboration and collaboration with learning (Matusov, 1999). UREs often occur within CoPs. For example, the development of scientific culture occurs within social learning and participation in inquiry (López Cerezo & Cámara, 2007). Within research settings, students share a domain; they interact with peers, graduate students, and faculty; and they work toward shared goals using shared disciplinary practices.

With the intertwined nature of UREs and CoPs, it is important to remember individuals within the communities (Godin & Gingras, 2000). To genuinely belong to a CoP, individuals must be connected to the community or be in the process of building their sense of community (McMillan & Chavis, 1986). McMillan and Chavis (1986) highlighted aspects needed for an individual to develop their sense of community including 1) a sense of belonging and being regarded by other community members; 2) a sense of influence and trust of authority; 3) an ability to satisfy the needs of the community; and 4) a set of shared experiences (McMillin & Chavis, 1986; Nistor et al., 2015). Just as the disciplinary practices are rooted within the culture of the discipline, CoPs provide opportunities for participants to become integrated in the process and constructs of their discipline. However, without a sense of belonging, an individual may not be integrated into the CoP. In other words, without a sense of belonging, an individual may not identify with the culture of their discipline. Given this, we posit that engagement in a community of science or mathematical practice is necessary for preservice STEM teachers to come to identify with their discipline and foster SEP or SfMP in their classrooms.

Learning within Research Experiences

There are multiple forms of research opportunities for students at all levels of education: undergraduate research experiences (UREs), course-based undergraduate research experiences (CUREs), and research experiences for in-service and preservice teachers (RETs). While each research experience may have different goals, participation groups, and demographics, they all have a common thread of providing opportunities for individuals to participate in research, promoting STEM disciplinary knowledge and practices, and integrating participants into STEM culture (NASEM, 2017). In addition to the goals above, UREs and CUREs focus on increasing participant retention and engagement in STEM majors (NASEM, 2017), while RETs focus on translating research experiences to classroom pedagogy and developing relationships with university settings (National Science Foundation (NSF), 2020a).

Undergraduate Research Experiences (UREs). Undergraduate research experiences (UREs) often occur within individual research groups which engage a handful of participants in authentic research directed by the faculty (Auchincloss, et al., 2017; NASEM, 2017). Most UREs allow for one-on-one mentoring between the participant and faculty mentor (Linn et al., 2015). Participants are selected or self-selected to participate (Auchincloss, et al. 2017), and UREs can occur over a school year, a summer, or extended over multiple years. Often UREs allow undergraduates to learn

from more experienced faculty and graduate students through apprentice-style programs outside of class time and in research spaces (NASEM, 2017). UREs are more common in science disciplines than in mathematics disciplines (Gallian, 2012; Groth, et al., 2016); therefore, most of the evidence on outcomes of UREs is based in the science disciplines.

UREs increase participant graduation and retention rates and interest in pursuing advanced degrees (Sadler et al., 2010). Beyond encouraging participant retention, UREs have documented learning gains, including learning lab techniques, personal development, research process skills (Lopotto, 2004; Kardash, 2000; Russel et al., 2007), scientific problem-solving skills (Lopatto, 2004; Russell et al., 2007; Seymour et al. 2004), interest in science (Hunter et al. 2007), and sense of responsibility (Hunter et al., 2007). UREs build a stronger understanding of the research process (NASEM, 2017) and provide real-world connections to coursework (Hunter et al., 2007; Hurtado et al., 2009; Miller & Walston, 2017). In addition, UREs support the intellectual growth of participants as they collaborate and share opinions with fellow students and their faculty mentors (Hunter et al., 2007). UREs allow students to think like scientists and learn how to communicate scientific ideas (Seymour et al., 2003). This learning and collaboration are often supported by a faculty member who mentors how research is completed within their research setting (Hunter et al., 2007).

As noted above, UREs are less common in mathematics. For example, a comparison of NSF-funded Research Experiences for Undergraduates (REU) in 2020 noted 38 REU sites in mathematics compared to 71 chemistry, 67 physics, and 136 biology REU sites (NSF, 2020b). However, there has been a push to incorporate authentic mathematics research for undergraduates with REU programs highlighted by the American Mathematical Society (American Mathematical Society, 2020) and mini-grants offered through the Center for Undergraduate Research in Mathematics (Center for Undergraduate Research in Mathematics, 2020). Mathematics UREs look different from science UREs. Instead of focusing on data collection and experimentation, mathematics research focuses on addressing questions about the structure of mathematics systems or applying mathematics to solve practical problems (Subcommittee on Undergraduate Research, 2006). Also, mathematics URE research takes time to deeply think about mathematics problems and questions; therefore, mathematics UREs are less likely to create published works (Subcommittee on Undergraduate Research, 2006). However, similar to science-based UREs, mathematics URE participants note the value of the experience (Connolly & Gallian, 2007), increased participation in graduate school (Connolly & Gallian, 2007; Garcia & Wyels, 2014; Leonard, 2008), creation of research presentations (Das, 2013; Gallian, 2012; Leonard, 2008), development of mathematics research skills (Connolly & Gallian, 2007; Das, 2013), and enhanced ability to communicate mathematics (Leonard, 2008). Das (2013) discussed their experiences and challenges with Academic Year Research (AYR) in mathematics and noted the potential participant benefit of connecting with faculty. However, most papers on mathematics research experiences are program descriptions with benefits outlined through a handful of student quotes. More empirical research is needed on mathematics UREs, and research specifically should focus on the integration of participants into mathematics research culture and the development of mathematic knowledge and practices.

Course-based Undergraduate Research Experiences (CUREs). CUREs tackle novel research questions in a more structured format than apprentice-style URE programs (NASEM, 2017). Participant research experiences are connected to coursework, both electives and required, with one faculty engaging with many students in research at one time (Auchincloss, et al., 2017;

NASEM, 2017). Participation is open to all students eligible to take the course (e.g., completed prerequisites), and research occurs during class time in a teaching laboratory (Auchincloss, et al., 2017). It is unclear how many CUREs are built into course curricula for undergraduates in science and mathematics disciplines as most research has focused on describing specific CURE programs and outcomes. Documented benefits of science discipline CUREs include higher STEM graduation rates (Rodenbusch et al., 2016), development of discipline specific content knowledge, increased interest in discipline (Kortz & van der Hoeven Kraft, 2016; Nadelson et al., 2010), development of technical skills (Kortz & van der Hoeven Kraft, 2016) and real-life connections to coursework (Miller & Walston, 2010).

Authentic mathematics research opportunities for undergraduates sometimes occur as experimental mathematics courses. In this case, the course curriculum is similar to that of CUREs in the science disciplines and explores mathematics by thinking experimentally through discovery of patterns, development of conjectures, and creation of algorithms (Brown, 2014). Experimental courses work on complex solved or unsolved problems (Brown, 2014). Benefits of experimental math courses include “ownership” of mathematics ideas and concepts, and a stronger articulation of mathematics ideas (Brown & Yürekli, 2007). In addition, students participating in experimental mathematics build their ability to question and explore mathematics concepts and view math beyond memorization of formulas or plugging in numbers (Brown & Yürekli, 2007; Pudwell, 2017). More empirical research is needed to confirm course outcomes and how curricula influence students’ understanding of mathematics concepts and practices.

Research Experiences for Teachers (RETs). RETs are specific research programs, often occurring over the summer, that engage preservice and/or in-service teachers in authentic research that can be applied to their pedagogy (NSF, 2020a). RET participants often self-select based on personal interests and goals. Preservice teachers or in-service teachers participating in UREs or RETs have unique learning outcomes. In-service teachers often enter their research experiences with specific goals, which are related to outcomes of the research experience (Faber, et al., 2014). Participants entering with goals focused on conventional teaching are less functional within the research settings than those hoping to integrate research into their courses (Faber, et al., 2014). While individual goals may influence what a participant gains from their research experience, many positive outcomes are likely, including increased understanding of science content knowledge and methods (Boser & Faires 1988; Cutucache et al., 2017; Herrington, et al., 2016; Raphael et al., 1999; Westerlund, et al., 2002), renewed excitement in subject matter, changed attitudes toward inquiry-based teaching practices (Herrington, et al., 2016), and increased awareness of connections between science and education through genuine examples and experiences (Boser & Faires, 1988; Buck, 2003; Raphael et al., 1999; Westerlund, et al., 2002). First-hand scientific experiences increase likelihood of desirable changes in pedagogical beliefs and practices (Miranda & Damico, 2013; Windschitl, 2004). In addition, RETs support pedagogical change by building confidence in use of scientific instruments, which may increase the likelihood of incorporating similar scientific processes into curriculum (Buck, 2003; Cutucache et al., 2017; Dresner & Worley, 2006). RETs value extends beyond content knowledge and pedagogical change. RETs build partnerships with scientists and fellow participants as resources when participants return to their classrooms (Dresner & Worley, 2006).

Most RETs programs are focused on recruiting science in-service teachers. Some RETs have recruited both math and science teachers (Boser & Faires, 1988). However, currently there is a

dearth of literature on the experiences of participants in mathematics RETs, because they are so few.

Research Experiences and Culture. All forms of research experiences are an effective way to integrate participants into the process of disciplinary research. Time within the research setting is an important consideration, as the more time spent in a research setting enhances outcomes (Linn et al., 2015). Individualized research experiences, like those offered through URE and RET programs provide more time to develop and learn science and mathematics processes; however, the culture and social structures within these research settings can impact student outcomes. Participants within science laboratories are embedded in the culture of science (Westerlund, et al., 2002). Research experiences increase participant confidence to practice research and contribute to science and mathematics through building professional relationships with faculty and peers (Baum et al. 2017; Hunter, et al., 2006). Research experiences hold the potential to shift participant identity and sense of belonging, allowing participants to ‘feel like a scientist’ (Hunter, et al., 2006; Seymour et al., 2004) or ‘feel like a mathematician.’ This finding is shared with other research studies, highlighting the authentic participation and integration into the disciplinary community that occurs over time within an URE or RET (Faber, et al., 2014; Westerlund et al., 2002). UREs and RETs develop a participants’ sense of community within a CoP. As a participant becomes more integrated into the research setting, participants feel like they belong (Faber, et al., 2014); an individual’s identity evolves to fit within a specific research-oriented CoP (Lave & Wegner, 1991).

CoPs include relationships within settings. Studies of research experiences demonstrate that the relationships with faculty and peers impact learning gains and beliefs within UREs and RETs (Burgin & Sadler, 2016; Eagan et al., 2013; Southerland et al., 2016). These relationships may be influenced by the culture developed within each research setting’s CoP. For example, in a study of a summer high school research apprenticeship, scientific laboratories that seemed to support nature of science learning included 1) a variety of methods used during research, 2) an opportunity for students to make meaningful contributions to research as a team member, and 3) a faculty mentor who discusses the nature of science with their students (Burgin & Sadler, 2016). These findings demonstrate McMillan and Chavis’s (1986) four aspects of the sense of community framework (i.e., sense of belonging, trust of authority, ability to contribute; shared experiences).

Similarly, aspects of CoP are reflected in other URE studies. Russell et al. (2007) noted students involved in the culture of research, including attending conferences, mentoring peers, and authoring papers, had more positive outcomes than those that were less involved within laboratory settings. These outcomes included increased confidence in research skills and interest in advanced degrees in the STEM fields (Russell et al., 2007). UREs reflect the legitimate peripheral participation that facilitates a new member’s integration into the CoP (Lave & Wegner, 1991). With a number of studies noting the development of confidence in laboratory work and scientific practices (Harsh et al., 2011; Hunter et al., 2006; Russel et al., 2007; Westerlund, et al., 2002), URE structure may influence a student’s sense of community and build research identity (Buxton, 2001). Socialization into the community provides validation and recognition of the individual’s new identity (Hurtado, et al., 2009).

In addition, collaboration between mentors and students to develop personalized research projects based upon student interest and skill-sets foster student confidence while conducting research and long-term interest in STEM careers (Harsh et al., 2011). The design of research experience programs and mentorship style (e.g., collaboration) play a role in student outcomes

(Harsh et al., 2011). The research setting culture and relationships between mentors and students can enhance collaborative learning and develop the competence needed for success within the discipline (NASEM, 2017). While aspects of positive mentoring relationships have been considered in previous research, few studies have considered which aspects of mentoring are important for positive student outcomes (NASEM, 2017).

As discussed, research experiences often occur within communities of practice. They provide opportunities for students to engage within a research domain, develop relationships and collaborations, and learn the practice of researchers. Through these unique interactions, undergraduates have opportunities to build their personal identities as researchers and learn how to engage in the practices of the scientific community (Lave & Wegner, 1991; Linn et al., 2015). CoPs within research settings and the relationships between research faculty and students that develop within the CoPs enhance student outcomes. Mentoring within UREs and RETs is an important aspect of learning within research settings. Mentors have many roles within research laboratories: coordinating research tasks, monitoring progress, guiding research, fostering skill development, facilitating participation, building networks, and enhancing student identification with the discipline (NASEM, 2017). Strong mentors are able to rotate between shifting roles but also provide students with opportunities to become contributing members to the research setting (Faber et al., 2014). These mentors engage students in research practices, emphasize teamwork, allow mastery of techniques, communicate results, and slowly increase the responsibility of the students over time (NASEM, 2017). UREs and RETs have the potential to build participant agency (Faber, et al., 2014; NASEM, 2017; Westerlund et al., 2002), and this sense of agency is likely connected to the mentoring relationship developed over the course of the research experience.

Research Experiences and Preservice Teachers. Few preservice teachers apply for URE programs or present authentic research at conferences (Manak & Young, 2014). Barriers to preservice teacher participation in UREs or RETs include the amount of time to complete teacher accreditation and a focus on finding teaching opportunities to enhance professional resumes (Manak & Young, 2014). Therefore, there is limited knowledge on how mathematics or science disciplinary research experiences impact science and mathematics preservice teachers. Research describes similar outcomes from preservice science teacher research experiences as in-service teachers participating in RETs, including increased procedural, content, and technical knowledge, comfort with research unknowns, and confidence in open-ended experimentation (Brown & Melear, 2007; Raphael et al., 1999). The Maryland Collaborative for Teacher Preparation was developed for mathematics and science preservice teachers and noted similar gains in confidence and disciplinary content knowledge, but also shifts in pedagogical viewpoints toward inquiry (Langford & Huntley, 1999). O'Hanlon et al. (2015) describe the development of preservice mathematics teacher participants' procedural skills and changes in pedagogical orientations toward more discovery-based lessons during a summer research experience. Preservice teachers, embedded in authentic research experiences, learned science by doing and encountered relevant examples of how mathematics and science connect to real-life, which could be incorporated into their pedagogy (Raphael et al., 1999). Other research experiences for preservice teachers provide training in action research (Groth et al., 2016). Action research was perceived as useful to preservice teachers because it develops the skills of reflection on teaching in tandem with increasing content knowledge (Groth et al., 2016; McIntyre et al., 2015; Myers et al., 2018). Most of the literature on education action research focused on developing pedagogical skills of reflection for preservice education majors (e.g., English education, special education, middle school

education); however, less attention was given to the growth of disciplinary practices understanding while conducting research projects. Teachers with long-term research experiences were more likely to use inquiry-based pedagogies in their classrooms (Windschitl, 2004), connect their coursework with real-life examples, have increased confidence in subject content and procedures, and build useful relationships with faculty and researchers (Raphael et al., 1999). We would hope scientific and mathematics content coursework would provide a foundation for building disciplinary practices understanding; however, we argue that traditionally taught content courses do not provide the experiences necessary to develop a robust understanding of inquiry as action or the disciplinary practices. For example, Windschitl (2004) noted traditional science content coursework did not enhance preservice teacher scientific argumentation skills. Therefore, without participation in authentic research, teachers may fail to develop understanding of the scientific enterprise (Faber, et al., 2014), which we argue will undermine their ability to implement the standards by engaging students in disciplinary practices.

A Call to Action

Since the development and adoption of the CCSSM and NGSS, science and mathematics teachers are expected to teach inquiry through SEP or SfMP, respectively. Many studies demonstrate the potential benefits of UREs, including increased interest, understanding, and knowledge within scientific and mathematics disciplines (NASEM, 2017). However, few have considered how preservice teachers develop disciplinary practices, and research experiences seem like the most obvious setting in which they could gain experience practicing as a scientist or mathematician. It is unclear how many teacher education programs require a research internship in addition to discipline-focused methods coursework. Also, it is uncertain whether these internships imbed the foundations of scientific or mathematics practices within preservice teachers, which then extends into their teaching. While some studies have considered mentoring relationships within UREs and student experiences, very few studies have considered the culture of URE and understanding of disciplinary practices, let alone how the unique characteristics of research settings may impact student outcomes (NASEM, 2017). In addition, few studies have considered the long-term understanding and teaching integration of scientific and mathematics processes within classrooms.

Therefore, we call upon our STEM education community to engage preservice teachers in UREs and further explore UREs and their influence on preservice secondary science and mathematics teachers' understanding of their disciplines' practices. We argue that UREs allow preservice teachers to become acculturated into a community of practice that would facilitate deep understanding of the practices of their discipline, enabling them to integrate engagement in disciplinary practices into pedagogy. Therefore, we suggest that research experiences that allow preservice teachers to interact within their disciplinary community via RETs or UREs are likely to accomplish these goals. We hope to see an expansion of current knowledge of factors that allow preservice science and mathematics teachers to engage their students in their disciplinary practices, which may have implications for undergraduate preservice STEM teacher education.

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