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Big Ideas of Mathematics: A Construct in Need of a Teacher-, Student-, and Family-Friendly Framework

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ABSTRACT

Across multiple countries the term "big ideas" of mathematics has become a construct advocated as important for teachers' mathematical knowledge. Indeed, several policy or position statement documents about math learning in the United States (U.S.) have stated that "big ideas" of math is a crucial construct for teacher knowledge. With this study we sought to determine if there was consistency about this "big idea" construct that teachers of mathematics in the U.S. are advised to know. To this end, we conducted a content analysis of resources for U.S. teachers of preschool through grade 12. We determined that few resources defined a big idea and those that did lacked agreement with each other. Although most resources delineating big ideas cited Charles (2005) as the basis of their use of the construct, our analysis of the actual big ideas in each resource revealed inconsistent implementation of Charles' theoretical perspective. Thus, to move research and practice forward by more precisely defining and prioritizing this abstract construct we (a) clarified a definition, (b) specified five criteria, and (c) constructed a scholar- and teacher-friendly framework: The Big Ideas Framework. This framework consists of three ordinal levels to distinguish and prioritize the importance of big ideas based on relative size and power: Mighty Mega Math Ideas, Power Math Ideas, and Strong Math Ideas. Moreover, the big ideas construct has focused on Mathematical Knowledge for Teaching (MKT), whereas we urge the field to shift its theoretical perspective to value the entire construct or at least the two most powerful levels of the framework as aspects of Common Content Knowledge. In other words, we urge teachers and mathematics teacher educators to foreground Mighty Mega Math Ideas and Power Math Ideas with P-12 students and families to empower those we serve. Furthermore, given the dearth of peer-reviewed research about big ideas, we encourage a new branch of scholarship to analyze the impact of the practical recommendations we offered here.

Keywords: big ideas, teacher knowledge, math learning, teacher professional development, teacher education

Introduction

The importance of focusing on big ideas is widely advocated to support the teaching and learning of mathematics. The notion of discipline-specific big ideas can be traced back to Bruner's (1960) "fundamental ideas," where he argued that "knowledge . . . acquired without sufficient structure is knowledge that is likely to be forgotten" (p. 31). Similarly, Wiggins and McTighe (2005) argued that, regardless of the discipline, big ideas promote transfer; that is, they apply to future learning both horizontally (across topics) and vertically (across grade levels and courses). Moreover, using big ideas can facilitate "thinning out" an over-crowded curriculum and can "create opportunities to rethink and transform existing approaches to the teaching and learning of mathematics" (Siemon et al., 2012, p. 20).

The challenge is that curriculum standards in the United States (U.S.) are presented to teachers linearly (Hurst & Hurrell, 2014). In the U.S., the first standards documents put forth by the National Council of Teachers of Mathematics (NCTM; 1989) did not constitute a national curriculum as most countries use. These documents separated mathematics into what were called strands of *Geometry*, *Measurement*, *Data Analysis and Probability*, *Number and Operations*, and *Algebra* (NCTM, 1989, 2000). Current mathematics standards in each state are built from the *Common Core State Standards for Mathematics* (hereafter referred to as *CCSSM*; National Governors Association Center for Best Practices [NGA Center] & Council of Chief State School Officers [CCSSO], 2010). In Grades K to eight, standards are divided into four to five domains for each grade, whereas in high school the divisions are overarching "conceptual categories" rather than grade levels or courses. Domain titles and conceptual categories vary in their scope and are organized somewhat differently than the original strands, such as *Geometry*, *Measurement and Data*, *Counting and Cardinality, Number and Operations in Base Ten, Ratios and Proportional Relationships, Building Functions*. Each of these domains is divided further into clusters, which in turn, are divided into standards. These standards are the focus of the teachers' attention when instructing students and by which students and teachers are evaluated on state tests.

The quantity of standards range from a total of 24 in Kindergarten to 33 in eighth grade and 31 in high school Algebra. In spite of the intent of the *CCSSM* having been to "significantly narrow the scope of content in each grade and deepen how much time and energy is spent on major topics in the classroom" (Coleman et al., 2013, p. 3), it is commonly known in practice that the copious number of standards is problematic. Although some efforts have been made to help teachers connect standards vertically and horizontally, such as Achieve the Core (Student Achievement Partners, n.d.), the U.S. curriculum document is a checklist of discrete knowledge. With the focus on these narrowly defined standards separated out by domain within a grade, teachers teach these standards in an unconnected way, and therefore children learn it the same way (Boaler et al., 2017; Hurst & Hurrell, 2014). Siemon and colleagues (2012) suggested using big ideas to further 'thin out' the curriculum (p. 20), and Charles (2005) cautioned not to let the number of big ideas "balloon" (p. 12). The number of big ideas we found in our search ranged from as few as three (Small, 2009) to as many as 80 (Boaler et al., 2017).

To get a sense for how the term "big idea" has been used in prior and current documents related to mathematics teaching and learning, we searched for a variety of publications that have employed the term. Most of the publications we found were teacher educator-focused articles or reports and books aimed to improve teacher's knowledge, only some of which were peer-reviewed. Our search for big ideas yielded reports to government or grant agencies in several countries (Kuntze et al., 2011a; Morgan, 2012; Niemi et al., 2006; Siemon, 2022; Siller & Kuntze, 2011; Tout et al., 2015; YuMi Deadly Mathematics, 2016), popular press books (e.g., Boaler et al., 2021; Early Learning Collaborative, 2014; Schifter & Fosnot, 1993; Siemon et al, 2012; Small, 2009), professional organization books (Toh & Yeo, 2019; Zbiek, 2010, 2011, 2012, 2013, 2014), and proceedings of joint conferences for practitioners and scholars (Skalicky et al., 2007; Siemon, 2013; Watson, A. 2007; Watson, J., 2007; Worsley, 2011). In terms of peer-reviewed publications, we found practitioner articles (Charles, 2005; Clarke et al., 2012; Edwards, 2000; Ritchhart, 1999; Woodbury, 2000), research conference proceedings (Askew, 2015; Hurst, 2014; Kuntze et al., 2011b; Siller et al., 2011; Stehr et al., 2019;), and just five peer-reviewed articles in research journals (Askew, 2013; Greenes, 2009; Hurst, 2014; Hurst & Hurrel, 2014; Siller & Kuntze, 2011).

Although none of the explanations of the term big ideas used the word *power* within formal definitions, some used this word or idea in later paragraphs of the narrative text around big ideas to explain the importance of big ideas. Notice the use of the word *power* in each of the following, which we used italics to emphasize. For example, Carnine (1997) asserted that big ideas "have rich *explanatory and predictive power*, as students can use them in solving many different problems that on the surface appear to be unrelated" (p. 133). Ritchhart (1999) argued that teachers must "look forward to what they can give students *real power*," to "build *mathematical power*, and . . . opportunities. . . for making connections and supporting transfer" (p. 463). Boaler and colleagues (2017) explained that to determine their big ideas, "We also thought carefully about the ideas that get little attention in standards and curriculum, but that are *powerful for mathematical thinkers*" (p. 4). For Tout et al. (2015), "The concept of Big Ideas is *powerful* because it assists teachers in developing a coherent overview of mathematics . . . [and] enables students to develop a deeper understanding of mathematics and its interconnectedness" (p. 19). Wiggins and McTighe (2005) asserted that "a big idea is not 'big' merely by virtue of its intellectual scope. It has to have *pedagogical power*: It must enable the learner to make sense of what has come before; and most notably, be helpful in making new, unfamiliar ideas seem more familiar" (p. 70). Finally, according to Charles (2005), limiting the quantity on which to focus is "what makes the notion of Big Ideas *so powerful*" (p. 11). With our careful reading of these works, we noticed this theme of power as underlying the field's thinking about this construct, however, this has yet to be foregrounded in the meaning of the term itself.

What is a Big Idea and How Big is Big?

Given that the name of the construct of "big" ideas is entirely based on an adjective related to size, we were surprised that few described the size or acknowledged the dilemma of just how big a big idea is. Boaler et al. (2017) did provide visual and narrative indications that not all big ideas are the same size or relative importance. Implicitly the authors communicated varied sizes of big ideas through network diagrams in which the nodes varied in size (Boaler et al., 2017). Askew (2013) described the size of a big idea in subjective terms that might evoke the Goldilocks principle as "big enough . . . but not so big that it is unwieldy" (p. 7). Charles (2005) expressed his dilemma that it was too difficult to articulate how big was sufficiently big to be labeled a big idea, yet like Askew he viewed particular ideas as being important but not "sufficiently robust to qualify as a big idea in mathematics" (p. 9). In a systematic literature review about big ideas, Askew (2013) concluded that there is no standard definition for a big idea of mathematics. A decade later as we sought the definition of "big idea," we found a wide range of specificity in terms of whether the term was used without definition, used with vague explanations around the construct, or with an explicit definition.

Surprisingly, the term "big idea" has been used with the article "the" in policy documents about what teachers must know, yet these documents failed to (a) provide "the" big ideas teachers must know and (b) define or explain what a big idea is (e.g., NCTM, 2000, 2014). Others used broad explanations. For example, Schifter and Fosnot (1993) described big ideas as "central organizing principles of mathematics with which students wrestle as they confront the limitations of their existing conceptions" (p. 24). Some described requisite characteristics or criteria without providing an explicit definition. For instance, Clements and Sarama (2009) identified three criteria which big ideas must meet; specifically, big ideas are "clusters of concepts and skills that are mathematically central and coherent, consistent with children's thinking, and generative of future learning" (p. 1). Alternatively, Kuntze et al. (2011a) asserted that big ideas must possess the following four characteristics: 1) have a high potential for encouraging mathematics learning with understanding of conceptual knowledge, including orientation, linking, and anchoring of knowledge; 2) are relevant for building up knowledge about mathematics as a science; 3) support abilities of communicating meaningfully about mathematics; and 4) encourage reflection processes of teachers connected with designing rich and cognitively activating learning opportunities, as well as accompanying and supporting learning processes of students. These broad characterizations provide some sense of the construct, yet what the field needs is a shared theoretical perspective.

Charles' (2005) Theoretical Perspective of Big Ideas of Mathematics

Although Charles (2005) did not use the terms framework, theory, or theoretical perspective, we view Charles' definition of and criteria for the often-used construct of big ideas of mathematics as an underused theoretical perspective. In terms of a definition of a mathematical big idea, only Charles (2005) provided such a definition: "A Big Idea is a statement of an idea that is central to the learning of mathematics, one that links numerous mathematical understandings into a coherent whole" [capitalization in original] (p. 10). He then clarified his theoretical perspective by explaining phrases within the definition as well as specifying additional criteria not in the definition. For example, the term "statement" is in the definition and Charles emphasized it is crucial that the idea must be phrased in this way. A statement is a type of sentence that has a verb and a subject; it is also not a question (O'Brien, 2023). Charles was adamant that every big idea must have a name preceding it as a way to refer to it, not just the statement itself. In some work that comes after Charles (2005), the criteria of connections is used without further specification, whereas notice in the definition he quantified this with the adjective "numerous." Although numerous is a vague term, he acknowledged he found it difficult to codify how big or "robust" a big idea must be to be "central to the learning of mathematics" or how many "understandings" would be linked to be "sufficiently robust" (Charles, 2005, p. 9). Charles (2005) and Boaler et al. (2017) are among the few to acknowledge this quandary of how big is big or even that some ideas are bigger than others.

Some have pointed out that it may be impossible to determine a complete canon of ideas upon which professionals could agree (e.g., Boaler et al., 2017; Charles, 2005; Ritchhart, 1999). Some posit that it is important for teachers themselves to determine big ideas within their professional development and unit planning—and it is this process of collaboration and professional growth that is most important (e.g., Boaler et al., 2017; Ritchhart, 1999). Yet, as Boaler et al. (2017) recognized, most teachers and districts do not have the time or structures in place to foster this process approach, which is why they offered eight to ten big ideas in each grade. Moreover, it would behoove us to use the insights of a teacher who explained why it is important to provide big ideas to teachers: "big ideas I think need to come from someone who sees the big, big picture" (Clarke et al., 2012, p. 17). This teacher advocated that rather than teachers developing the big ideas, teachers need the field to provide big ideas as a starting point. This would make it feasible for teacher planning teams to focus on how to implement the ideas for their own students and contexts (Clarke et al., 2012).

In summary, Charles (2005) provided the most specified definition, supporting criteria and 21 big idea statements to form a theoretical perspective for the construct of big ideas (e.g., Askew, 2013; Boaler et al. 2017; Hurst & Hurrell, 2014; Siemon et al. 2012; Small, 2009). In spite of Charles (2005) having provided specificity and being universally cited, there is still little agreement in subsequent literature about what 'big ideas' are (Askew, 2013; Siemon, 2013). This seems to be due to the fact that although most documents discussing big ideas cite Charles (2005), they have not built on the specifics he offered in his theoretical perspective.

Big Ideas Are For Teachers

Many policy documents and articles assert that "big ideas" are crucial to developing teachers' content knowledge and their ability to effectively implement curriculum (Association of Mathematics Teacher Educators [AMTE], 2017; Hurst & Hurrell, 2014; Kuntze et al., 2011a, b; NCTM, 2000; Prawat, 1992; Toh & Yeo, 2019). Almost a quarter century ago, NCTM (2000) published the *Principles* *and Standards for School Mathematics*, which stated that teachers needed to "understand the big ideas of mathematics and be able to represent mathematics as a coherent and connected enterprise" (p. 17), without ever defining what a big idea was—except for mentioning "equivalence" and "multiplicative reasoning" as big ideas for Grades 3-5. Note the use of the article "the." A decade later, in the *CCSSM* (NGA Center & CCSSO, 2010), the term "big idea" does not appear anywhere in the document. Most recently in 2017, AMTE published the *Standards for Preparing Teachers of Mathematics*, which explicitly inserted the term into *Program Standard P.2. Opportunities to Learn Mathematics*, which states that

> An effective mathematics teacher preparation program provides candidates with opportunities to learn mathematics and statistics that are purposefully focused on essential big ideas across content and processes that foster a coherent understanding of mathematics for teaching (p. 29).

This document is for those who prepare future teachers, not the teachers who plan P-12 student instruction. This may signal a shift toward valuing and being more explicit about developing mathematics teacher educator understanding of big ideas in the US. Unfortunately, the AMTE (2017) document failed to provide mathematics teacher educators with a definition or criteria for "big ideas." Moreover, the document merely references Charles (2005) in the single grade-band section for upper elementary even while asserting that there must be vertical alignment of big ideas across grade bands: "Teachers preparing to teach in these grade-bands must develop mathematical knowledge that not only spans the grade levels but also provides them opportunities to understand big ideas (Charles, 2005) that unify mathematics across grade-band divides" (AMTE, 2017, p. 90).

There is also inconsistency regarding the terms used in these standards to refer to the same construct (i.e., six terms: *big ideas*, *essential big ideas*, *essential understandings*, *essential ideas, foundational mathematical ideas*, and *key mathematical ideas*) (AMTE, 2017, pp. 29, 47, 48, 50, 94) Although the AMTE document (2017) referenced Charles (2005) once, none of his 21 big ideas were included in the standards. The ideas selected for the AMTE standards (2017) seem to have come primarily from the *Essential Understanding Series* published by the affiliated organization of the National Council of Teachers of Mathematics and the *Mathematical Education of Teachers II (METII)* document (Conference Board of the Mathematical Sciences [CBMS], 2012). Those ideas taken from *METII* were phrased as "essential ideas" and those taken from NCTM were the smaller detailed "essential understandings" rather than the broader statements labeled "big ideas," despite the fact the P2 standard as quoted earlier denotes "big idea" would be the term with "essential" used as a modifier for emphasis of those big ideas as "essential big ideas."

Although the ultimate goal is for students to have a strong and coherent understanding of mathematics, the focus of the writing about this construct has been on teacher knowledge, teacher education, and teacher professional development. In other words, the focus has been on improving Mathematical Knowledge for Teaching (MKT), which includes Common Content Knowledge that all graduates of K-12 schooling are intended to know, but also multiple types of knowledge that is unique to the demands of teaching mathematics (Ball et al., 2008). Moreover, although big ideas of mathematics as a construct is meant to unify ideas within the entire discipline of mathematics (Charles, 2005), the genesis of the construct seems to have focused on the MKT of those who teach the elementary grades (e.g., Charles, 2005; Clements & Sarama, 2009; Ritchhart, 1999; Schifter & Fosnot, 1993).

Another and perhaps more crucial limitation of prior work, is that each of the peer-reviewed articles we found were commentaries or literature reviews that primarily built upon other commentaries or non-peer reviewed publications. Kuntze et al. (2011b) pointed out that peer-reviewed research studies on big ideas were limited, which remains the case more than a decade later. We found only three peer-reviewed publications that analyzed data; that is only three were empirical

(Stehr et al., 2019; Siller et al., 2011; Worsley, 2011). Each of these was a conference proceeding in which the data were university instructor surveys and/or interviews regarding the content they teach. Two of these studies—both at the university level mathematics or mathematics teacher preparation—had methodologies and findings that did not address "big ideas" with the meaning intended in the field, because the interviews or surveys asked for "areas of study" (Worsley, 2011) or referred to an entire domain of high school mathematics and K-12 mathematical practice of "modeling" as though it was a "big idea" (Siller et al., 2011).

The only peer-reviewed conference proceeding that used the term "big idea" in their study design asked instructors of secondary mathematics teacher education courses: "What are the goals or big ideas of this course?" (Stehr et al., 2019). Note the phrasing of the question was "big ideas of *this course*" rather than "big ideas *of mathematics,*" so it makes sense that instructor responses of mathematics pedagogy courses included general pedagogy ideas (e.g., exceptionality, race, gender) and some mathematics-related responses (e.g., integers, proportional reasoning; Stehr et al., 2019). These ideas are all important in such courses. However, even the mathematics-related "big ideas" in the findings of that study were "topics," which Charles (2005) stated are not big ideas.

Although many policy or commentary documents claim that research has demonstrated the use of big ideas for improved teacher and student learning, from our own search and others' systematic literature reviews (e.g., Askew et al., 2013), it seems scholars have staked and built upon claims based on citing articles accepted into *research venues* or popular press outlets, without being based on *research findings* of empirical studies accepted by *peer-review* prior to publication. We have yet to find any empirical studies published in peer-reviewed venues that evaluated the impact of big ideas of mathematics on teacher knowledge or student learning.

Purpose of Study

To be clear, from practical experience we believe just as strongly as those who have published before us that big ideas of mathematics are one of the important ways to facilitate mathematically proficient teachers and citizens. However, as scholars and mathematics teacher educators we need to strive for a standard of evidence, which can only occur if we foster some agreement about the terms and meanings of the construct itself (Leatham, 2019; Spangler & Williams, 2019). To provide a foundation for the field to conduct empirical studies of teacher and student knowledge in the future, we as a field need some clarity and shared understanding regarding the definition, size, and purpose of big ideas of mathematics.

Pepin and Gueudet (2014) define curriculum resources as items teachers use "in their day-to-day teaching, when they decide what to teach, how to teach it, and when they choose the kinds of tasks, exercises, and activities to assign to their students" (p. 132). So we turn to the resources used to inform those who are not academics to uncover what information about big ideas of mathematics are being communicated. Charles (2005) has been repeatedly cited in policy documents about big ideas of mathematics. This work was also the only one we have found to provide an explicit definition along with criteria and supporting examples that could be characterized as a theoretical perspective. So we return to this foundational work as a way to systematically assess resources designed since 2010 — when the *CCSSM* was published— to inform what big ideas are and as a way to promote mathematics as a coherent discipline. Given that teachers are told they must know "the big ideas," the purpose of this empirical study was to use a content analysis methodology to investigate these resources for how big ideas are being treated and portrayed. The specific research questions were:

1) To what audience were the big ideas directed? (RQ1)
2) How did each analyzed resource define or explain the construct of big ideas? (RQ2)
3) Were Charles' (2005) criteria of centrality, naming and grammatical format satisfied? (RQ3)

4) Was there consistency within and across resources about the relative size of big ideas? (RQ4)
5) How well were big ideas used to organize or provide coherency for mathematics? (RQ5)

Methods

We used a content analysis method (Schreier, 2012) to analyze 22 publications designed to inform P-12 stakeholders in the U.S. about big ideas. These 22 publications consisted of 224 big ideas, which we primarily analyzed using Charles' (2005) theoretical perspective. Qualitative content analysis involves a systematic investigation of only selected aspects within a data set based on the particular research questions (Schreier, 2012). Unlike other qualitative methods that include analytic memos and creation of additional data, "QCA reduces data" throughout the process as researchers create and refine categories that support broader interpretations (Schreier, 2021, p. 7). Validity in QCA is viewed as the "extent that your categories adequately represent" the data (Schreier, 2012, p. 7). Sample selection criteria and details of analysis for each research question follow.

Sample Selection Process

Given that the literature review revealed that teachers are supposed to "know the big ideas," and our concern for actual teaching practice, we sought publications for our data analysis whose target audience were teachers or P-12 students, not teacher educators or scholars. For example, neither a special issue of a research journal nor the AMTE (2017) *Standards for Preparing Teachers of Mathematics* would fit our target audiences of readers who are P-12 students or teachers. Of course, teacher educators might use the publications we analyzed and scholars and teacher educators would refer to the sources we cited in the literature review, However, our goal was to find consistency about the construct of big ideas as it is being communicated to teachers and students to be used in P-12 schools. We considered the following as potential publications: P-12 standards documents, K-12 student textbooks, methods textbooks for teaching mathematics, textbooks of mathematics for future teachers, books published for teachers, and popular press books about mathematics.

We attempted to find every possible publication we could with the intent to then reduce the number of data sources to one to three publications for each audience (teacher or students), grade band, content, and publication type. The data we analyzed, however, were the only ones we found that met the criteria. Thus, we reported on all the data sources meeting the following criteria: (a) U.S. audience; (b) Teacher or student as the target audience (not scholars or teacher educators); (c) The term "big ideas" was used in the title or within the text and big ideas were delineated; (d) 2010 or later publication date; (e) Ensure vertical alignment with all grade bands represented: Early childhood, (P-2), Intermediate (3-5), Middle Childhood (6-8) and High School (9-12); (f) For horizontal and vertical alignment, domains (term used in *CCSSM*; NGA Center & CCSSO, 2010) or strands (term used in NCTM, 2000) were represented across grade bands; and (g) Each type of publication was represented: mathematics textbooks for future teachers, methods textbooks for mathematics teaching (hereafter referred to as "methods textbooks"), mathematics textbooks for P-12 students, or professional development resources about mathematics.

Publication types for which we searched but that did not meet the other criteria included P-12 standards, mathematics textbooks for P-12 students, mathematics textbooks used to teach future teachers mathematics content, and methods textbooks for teaching secondary mathematics. Although one methods textbook covered Grades 7-8 of secondary mathematics, we were unable to locate a methods textbook for Grades 9-12 of secondary mathematics. Nor did we find any mathematics textbooks used in mathematics departments to teach mathematics content to future teachers that used the term "big ideas" (even after consulting colleagues who teach such courses).

We also sought textbook series for P-12 students. Although there is a student textbook series called *Big Ideas Math* (Larson Texts, 2013-2018), in the preview copies, we were not able to find any mention of the word big idea within the textbook nor did we receive correspondence after emailing the publisher and author to inquire where the big ideas were located. The omission of actual big ideas from the textbook *Big Ideas Math* was also confirmed by a teacher who had taught from this textbook.

Given the importance of standards and readers' familiarity with such documents, we detail in chronological order more about why each standards document did not meet the criteria. NCTM (2000) standards from a generation ago did not meet the publication date criterion and is no longer used by teachers even though teacher educators and scholars may continue to use that document. *CCSSM* (NGA Center & CCSSO, 2010), which is used by teachers, does not use the term big ideas anywhere in the document. The AMTE standards (2017) is a document designed for mathematics teacher educators and program directors, so it did not fit the target audience of teachers or students. Thus, these standards documents were not considered as data sources of the study, although we used these in the literature review and discussion due to their importance. As is commonly expected in a publication-based content analysis, the sample is listed in alphabetical order in Table 1.

The reputable Erikson Institute's P-2 book (The Early Math Collaborative, 2014) and highly popular Van de Walle et al. (2019) K-8 methods textbook in Table 1 were stand-alone publications in which all covered grades were contained within a single book. In contrast, the NCTM publications (2010-2014) explicitly proclaimed in the titles that these are part of a series. This series offers a set of books for each grade band (P-2, 3-5, 6-8, and 9-12). This is consistent with the definition of series: "a number of things or events of the same class coming one after another in spatial or temporal succession" (https://www.merriam-webster.com/dictionary/series). The Boaler et al. (2017-2021) publications also fit the definition of a series, because the series consists of nine books, one for each grade from Kindergarten to Grade 8. To ensure that a resource was the unit of analysis and reflected vertical and horizontal alignment, we considered each entire series in which it took multiple publications to cover domains and grade bands as a single resource comparable to stand-alone publications that spanned domains and grade bands. Consequently and henceforth, we refer to each stand-alone publication and each series as a resource, resulting in four analyzed resources.

To focus reader attention on the resource type and grade band rather than authors, we refer to *Big Ideas of Early Mathematics* as P-2 Methods Textbook (P2MT), *Teaching Elementary and Middle School Mathematics Developmentally* as K-8 Methods Textbook (K8MT), *Essential Understanding Series* as P-12 Professional Development Resource (P12PD), and *Mindset Mathematics: Visualizing and Investigating Big Ideas* as the K-8 Professional Development Resource (K8PD).

Intended Audience of Selected Resources

Selection of the sample based on the audience is both a process we should report in the methods and also as one of our research questions, so we describe this here—RQ1: To what audience were the big ideas directed? The method for this content analysis was a review of the introduction and preface of each resource to select quotations that related to the intended audience. If no such information was found in those sections, then the table of contents, index, where big ideas were stated, and other pages were examined until the audience was found. All authors discussed until consensus in order to reduce these data to representative quotations. This information is provided in Table 2. We were only able to find one student textbook that used the term "big ideas" in the title. However, no big ideas were stated within the textbook content to speak directly to students or assist teachers to make these connections. Therefore, in every resource in our sample, teachers were the intended audience with the purpose to improve teachers' mathematics knowledge or MKT (RQ1). Table 2 provides evidence for each resource along with the scope of grades addressed.

Table 1

Publications in the Sample

Publication
Barnett-Clarke, C., Fisher, W., Marks, R., & Ross, S. (2010). *Developing essential understanding of rational numbers for teaching mathematics in Grades 3–5* (R. Charles, Ed.). In R. M. Zbiek (Series Ed.), Essential understanding series. National Council of Teachers of Mathematics.
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Table 2

Target Audience of the Big Ideas Construct in Each of the Sources

Resource	Audience and Who Should Own the Big Ideas	Evidence
P2MT	Teachers Future and Current	In the title: *Big Ideas of Early Mathematics: What Teachers of Young Children Need to Know*
K8MT	Teachers Future and Current	• In preface: "We believe that teachers must…We are hopeful that you will find that this book is a valuable resource for teaching and learning mathematics" (p. xiii). • "Some of you will soon find yourself in front of a class of students; others of you may already be teaching" (p. 1)
K8PD	Teachers	"We hope that our ideas will initiate rich conversations between teachers about the big ideas and the connections that relate them to each other. If you don't have colleagues to discuss the ideas with, (or even if you do) our youcubed Facebook group … is a lovely space for collegial discussions" (p. 10).
P12PD	Teachers	In Preface of each book: "Each volume in the series invites teachers who aim to be not just proficient but outstanding in the-classroom—teachers like you" (p. vii).

Data Analysis of Reported Big Ideas

Based on the inconsistencies we found in our initial literature review, we understood there would not be agreement as to which big ideas should be taught nor that there could be a canon of big ideas (Boaler et al., 2017; Charles, 2005). Thus, we did not seek to develop a coding scheme or an analytical framework that we could use to list or categorize every big idea in mathematics. Instead, the main purpose of this content analysis was to look for consistency and agreement within and across resources about big ideas as a construct, with the resource as the unit of analysis. This unit of analysis at the resource level is to inform the field whether a teacher learning from one resource would have the opportunity to develop similar ideas as a teacher who learned from a different resource. This is so that they would have a shared understanding as the basis for shared instructional planning. Specifically, each resource was analyzed for the meaning and relative size of big ideas, whether these met Charles' (2005) criteria, and how well big ideas were used to organize or provide coherency for mathematics and connections in mathematics.

As in the discipline of mathematics, a way to disprove a conjecture is to look for a single counterexample. Thus, in each analysis our main approach was to look for consistency of adherence to the criteria set forth in Charles' (2005) theoretical perspective and to report counterexamples within and across resources. Although K8PD (Boaler et al., 2017-2021) consisted of separate publications, the same big ideas were published in their summary document, available open source to the public as *What is Mathematical Beauty?* (Boaler et al., 2017), and in each grade-specific publication the authors encourage teachers to access this summary document to understand the big ideas applicable in other grades. Thus, for the purpose of this analysis, we analyzed this summary document as the resource K8PD. In contrast, NCTM did not provide such a summary document that stated all big ideas in P12PD, so we obtained the big ideas from each analyzed book. For our purpose of assessing consistency within a resource, analyzing most of these books adhering to criteria (e) and (f) as described in sample selection was sufficient (n=12). Our purpose was not to code every big idea presented in a resource, but rather to obtain evidence of consistency or inconsistencies.

To address RQ2 and 3, the quotations of explanatory text about the big ideas from each resource were analyzed and compared to determine whether these met Charles' (2005) criteria and how to categorize the character of the explanations when these did not meet Charles' criteria. An iterative process of selecting quotations that might serve as examples and counterexamples of consistency were grouped and discussed until consensus in terms of similarities and differences among the examples and how to name these categories (which in other mathematics education research studies might be called a theme). The first two coauthors then verified that no other categories were used and sought at least one example of each category from each resource. For the resources without examples in any category, those resources were checked again to confirm that nothing was overlooked.

To answer RQ4, the first author selected examples from every resource that might reflect a range of sizes. Then, all coauthors reduced the number of examples to three for each resource and came to consensus on the relative sizes. Finally, for RQ5, coauthors counted the number of big ideas, identified the structural divisions of the resource and discussed the justifications for the case of a big idea that we expected to find in all grade bands across domains (as described in the findings). Next, the first two authors independently read each big idea looking for explicit (exact words used) and implicit (synonyms or ideas used) evidence of the example case. During discussion of the 224 big ideas for RQ5, only one compose/decompose related big idea was missed by one author and the one disagreement was resolved through consensus.

Findings

The audience of each resource we found were teachers (RQ1), which was addressed in the methods section due to its overlap with reporting of the sample selection. Each of the remaining research questions were addressed in the order in which they were numbered: definition (RQ2), criteria (RQ3), how big is a big idea (RQ4) and whether the resources were organized around big ideas as recommended (RQ5).

Definitions of Big Ideas (RQ2)

Table 3 provides the definition or explanation each resource used to inform teachers what a big idea is (RQ2). In column two we summarized our interpretation of how the big idea was defined or explained. As the second column in Table 3 details, one resource defined big ideas, two explained around big ideas without actually explicating a big idea, and one provided neither an explanation nor a definition. Although K8PD stated the overarching reason for big ideas is to share the coherence of mathematics as a subject, it seems that in an effort to meet teacher's needs who must focus on grade-level standards, the immediate goal of the resource was to provide coherence within a grade level because the structure of the K8PD big ideas emphasize connectivity of the big ideas within each grade-level. The definition in P12PD focuses or frames big ideas as topic-based connections. Notice in Table 3 that K8MT implied that big ideas are something other than separate skills or concepts. Yet this resource refers to "lists" almost as if these are sufficient to provide the coherence for teachers' mathematical knowledge. This methods textbook stated the importance of big ideas; however, fails to define or explain what big ideas are. See Table 3; K8MT.

Criteria of Big Ideas Not Always Satisfied (RQ3)

Charles (2005) stated three criteria of big ideas. One criterion was that a big idea should have a name that is not the statement itself. Another criterion was that it needed to be central to mathematics and connect many smaller ideas. The third criterion was a grammatical expectation that a big idea be in the form of a statement and convey an "essential mathematical meaning" (Charles, 2005, p. 10). We next provide the findings related to these criteria (RQ3). The criterion of centrality and connections required several additional analyses to foster reliable and trustworthy interpretations.

Table 3

Definition and Names of Big Ideas in Each Resource

Source	Definition Character	Evidence	How Big Ideas Referenced
P2MT	Explanation around big ideas	• *Mathematically central and coherent.* **Big ideas convey core mathematics concepts and skills** that can serve as **organizing structures** for teaching and learning during early childhood years. • *Consistent with children's thinking.* • *Generative of future learning.* • *Comprehensive.* • *Thoughtful about content.* • *Developmentally organized.* • *Flexible (pp. 4-6).*	Unnamed: Idea Itself
K8MT	No Definition No Explanation	• No definition • Term "Big Idea" not indexed • The only introduction to big ideas occurs in in a callout of a page image: "Much of the research and literature espousing a student-centered approach suggests that teachers plan their instruction around big ideas rather than isolated skills or concepts. At the beginning of each chapter in Part II, you will find a list of the big mathematical ideas associated with the chapter" (p. xviii).	Unnamed: Idea Itself
P12PD	Definition; connects topics	• "The big ideas are mathematical statements of overarching concepts that are **central to a** mathematical **topic** and link numerous smaller mathematical ideas into **coherent** wholes" (p. viii). • "The books call the smaller, more concrete ideas that are associated with each big idea *essential understandings*" (p. viii).	Numbered Locally
K8PD	Explanation around big ideas; connects to other big ideas	• No definition • Explanation stated: "**big ideas are connected to one another within grade levels**, these 'connections give mathematics **coherence** which supports all students in making sense, as students draw on what they know about one big idea to learn about another" (p. 5). • Network diagrams visually communicate which big ideas are connected to each other within a grade.	Unnamed: Idea Itself

Big Ideas Need a Name Criterion

Column four of Table 3 characterized how the resources referenced their big ideas. Had any resource named a big idea prior to the statement of the big idea, we would have used the term *Named*. Resources did not name the big ideas prior to giving the big idea in its entirety. Charles (2005) cautioned against using the "idea itself" as a proxy for a name, so we coded these in Table 3 as *Unnamed: Idea Itself*. P12PD numbered each big idea within the book in which it was written, which we coded as *Numbered Locally*. In other words, even for a topic that was addressed in successive grade-bands (i.e., K-2, 3-5, 6-8 and/or 9-12), the numbering was only a valid reference within that grade-band specific topic publication. For example, even though the topic carried through the resource across grade bands, "Big Idea 3" was a different big idea in each publication. Moreover, potentially similar big ideas in different grade-band publications might be numbered with a number in one grade band, but a different number in another grade band. Thus, use of numbering would interfere with teachers or mathematics coaches being able to vertically align and recognize the coherence and building of big ideas of a topic *across* grade-band barriers within that resource.

Grammatical Format Criterion

According to Charles (2005) a big idea must satisfy the grammatical criteria of being a statement and be meaningful. We reviewed each resource to determine the grammatical structure of ideas labeled as "big ideas" and provide these findings in Table 4. Statements are not questions and they must have a subject and a verb (Obrien, 2023). Column two displays an example from each resource that satisfied the criteria of Charles (2005) and stands alone to provide information about a mathematical idea. Column three satisfies the grammatical criterion of being a statement but lacks the criterion of coherence or ability to stand alone as a resource for understanding. In Charles' (2005) words, his intention was that if written as a statement, it would have "the essential mathematical meaning of that idea" (p. 10), yet each resource had statements that did not do so. In other words, Column two is broad and usefully applicable to many situations, so it has power, whereas Column three is broad to the point of not being mathematically useful (Charles, 2005).

Columns four and five display excerpts from resources in which the stated "big ideas" were neither sentences nor statements. These grammatically consisted of questions (a type of sentence) or phrases. We categorized several of the stated big ideas formatted as phrases to be mathematical topics (e.g., Families of Functions) in Column five, whereas in Column four we documented other stated big ideas that we did not recognize as topics, but rather phrases with the grammatical structure of gerunds or present participles (e.g., "being flexible with numbers"; see Table 4). We also found that the two methods textbooks (P2MT and K8MT) provided some big ideas that consisted of at least two sentences or entire paragraphs rather than satisfying the criterion of being a statement.

As Column two of Table 4 reveals, in every resource we were able to find at least one example of a stated big idea that satisfied the grammatical and stand-alone meaning criteria. Yet, we found counterexamples of consistency for each resource. We found at least one example of a stated big idea in each resource that could not stand on its own to convey mathematical meaning, although it was grammatically a statement (see column three Table 4). The two resources for whom the intended audience was practicing teachers (P12PD and K8PD) also provided big ideas that were phrases, rather than statements (see Table 4 column 4 and 5). In P12PD we found phrases that we characterized as mathematical topics (see Table 4). In K8PD we found mathematical topic phrases as well as two other types of non-statements (see Table 4 Column 4): a) phrases that were not mathematical topics, but rather phrases with participles or gerunds indicating an action, and b) question sentence types. In contrast, the two resources that served as methods textbooks for future teachers as well as for teacher professional development—P2MT and K8MT— consistently satisfied the grammatical requirement of being a statement.

Table 4

Examples of "Big Ideas" that Show Varied Grammatical Structures

Resource	Statements that have stand-alone meaning	Statements without stand-alone meaning	Phrases with gerunds or participles that aren't math topics or sentences that are not statements	Phrases of Math Topics
P2MT[a]	"The same pattern structure can be found in many different forms" (p. v).	"Relationships between objects and places can be represented with mathematical precision" (p. vi).	--	--
K8MT[a]	"Percents are simply hundredths and, as such, are a third way of writing both fractions and decimals" (p. 406).	"Algebra is a useful tool for generalizing arithmetic and representing patterns in our world" (p. 299).	--	--
P12PD[b]	"Any rational number can be represented in infinitely many equivalent symbolic forms" (Barnett-Clarke et al., 2010, p. 8). "A written proof is the endpoint of the process of proving" (Sinclair et al., 2012, p. 8).	"Extending from whole numbers to rational numbers creates a more powerful and complicated number system" (Barnett-Clarke, et al., 2010, p. 7). "Expressions are foundational for algebra; they serve as building blocks for work with equations and functions" (Lloyd et al., 2011, p. 12). "Working with diagrams is central to geometric thinking" (Sinclair et al., 2012, p. 7).	--	"Expressions" (Lloyd et al., 2011, p. 9). "Families of Functions" (Cooney et al., 2010, p. 9)
K8PD[a]	"There are many ways to describe and sort objects" (p. 5). "A ruler is a number line" (p. 6).	"Representations and modeling structures help us see math" (p. 6).	"Being flexible with numbers" (p. 7). "Folding and unfolding objects" (p. 8). "What does it mean to divide fractions?" (p. 8). "What is a decimal?" (p. 7).	"Reasoning with proportions" (p. 8). "Thinking in powers of 10" (p. 8).

Note. [a]Each resource that is a stand-alone publication we referenced as a data source using the code as described in the Methods section (P2MT, K8MT, and K8PD), with the page number in a way to avoid emphasizing authors as the American Psychological Association (APA) would suggest if this were just a citation, yet any reader could still refer to the exact source. [b] Given P12PD consisted of multiple publications each of which had multiple authors, we used APA to cite within the table, even though our intention was not to call attention to authors.

Connections and Centrality Criteria

To determine how central or connected the stated big ideas were in each resource, we looked for evidence or counterevidence that the resources were organized based on the big ideas. Someone familiar with these resources might at first glance believe big ideas were the organizing feature. Table 5, however, clarifies how each resource was structured. No resource provided a chapter or section on big ideas to foreground the centrality of the big ideas to mathematics and how these connect across topics or grades. Some resources explained that a particular big idea was important because of its relevance in other topics. However, this was done as an extension and not as a centralizing feature. For example, P12PD followed a structure of Preface and Introduction that was the same in every book, followed by a chapter on the big ideas, followed by a chapter with explanations of connections to other mathematics —the degree to which these explanations provided connections varied by author. Each of the resources presented the big ideas only after the resource was structured or divided into grade bands or grades, then domains or topics, or some combination of these.

Are Big Ideas Consistently "Big"? (RQ4)

The only resource that showed some ideas were bigger than others was K8PD. This was implied, rather than explicit, by increased node sizes on network diagrams (where each node represented a big idea that was connected to other big ideas within that grade). None of the resources we analyzed provided an explanation of size criteria to clarify the meaning of the adjective "big." Thus, to answer RQ4 we reviewed the stated "big ideas" to look for some indication of size and consistency of size in relation to the terms used. Figure 1 provides a visualization of a continuum of sizes of ideas that were all referred to as "big."

What authors determined to be "big" ranged in size even within the same resource. This was true for every resource we analyzed. With this analysis, our goal was not to quantify or articulate the size of stated big idea ideas within or across resources. Rather, our intention was to determine if what was conceived of as a big idea within a resource seemed to be of similar size throughout that resource. The visualization in Figure 1 provides insight that there was inconsistency within and across resources about how big an idea should be in order to be labeled a "big" idea. When viewing Figure 1, it could be helpful to choose a resource and consider how the size of the quoted excerpts differ from small to large from bottom to top. This demonstrates evidence of inconsistency within a resource.

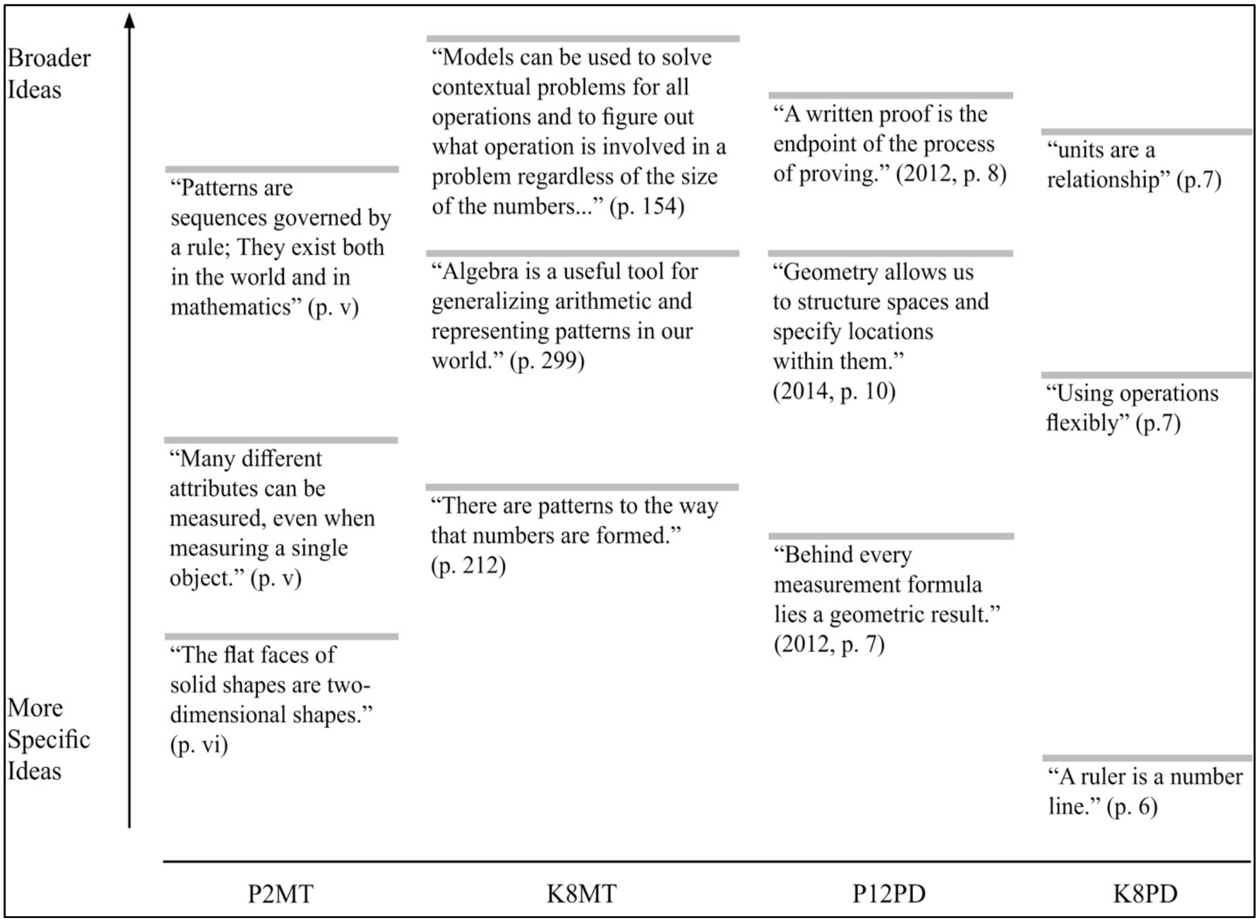
We also attempted to place these chosen excerpts in relation to each other across resources. See Figure 1 for this information. The line segment above each stated big idea indicates the relative position in the vertical dimension. Again, our intention was not to provide measurements for such sizes. We positioned the big ideas by their relative sizes in a visual format to provide a sense that big ideas varied in size and reveal the lack of patterns in the field for this construct.

How Well Have Big Ideas Been Used to Organize or Structure Mathematics? (RQ5)

The literature about big ideas and the analyzed resources explain that big ideas are meant to organize or structure teacher understanding of the mathematics to better understand and more efficiently work with standards and ideas. Thus, we looked for evidence that the resources were structured in a way that fostered this (RQ5). We investigated the overarching structural organization, including indications that redundancy was avoided. We did so in three ways. First, we analyzed how each resource structured the presentation of their big ideas. Second, we reported how many big ideas each resource provided. Third, to look for evidence of redundancies or hierarchical references to big ideas, we chose one example of a big idea, referred to as "bigger than" big by Boaler and colleagues (2017, p. 5). Given the purpose of big ideas is to promote connections (Askew, 2013; Charles, 2005), we chose an idea that was explicitly stated in more than one standard and domain of *CCSSM*: "compose and decompose."

Figure 1

Relative Size Comparisons of Big Ideas in the Analyzed Resources



P2MT:

"Patterns are sequences governed by a rule; They exist both in the world and in mathematics" (p. v)

"Many different attributes can be measured, even when measuring a single object." (p. v)

"The flat faces of solid shapes are two-dimensional shapes." (p. vi)

K8MT:

"Models can be used to solve contextual problems for all operations and to figure out what operation is involved in a problem regardless of the size of the numbers..." (p. 154)

"Algebra is a useful tool for generalizing arithmetic and representing patterns in our world." (p. 299)

"There are patterns to the way that numbers are formed." (p. 212)

P12PD:

"A written proof is the endpoint of the process of proving." (2012, p. 8)

"Geometry allows us to structure spaces and specify locations within them." (2014, p. 10)

"Behind every measurement formula lies a geometric result." (2012, p. 7)

K8PD:

"units are a relationship" (p.7)

"Using operations flexibly" (p.7)

"A ruler is a number line." (p. 6)

Resource Organization and Structure Belies Big Ideas are Overarching

Each of the resources presented the big ideas divided into either grade bands, grades, domains, topics, or some combination of these. Three of the four resources used grade bands or grades as the top-level category. No resource provided a chapter or section with big ideas as the top-most level of organization. Narratively, some resources explained that a particular big idea was important because of its relevance in other topics. However, the physical organization of each resource was structured first by traditional divisions of grades or domains/standards/topics, rather than the big idea being the top-most level.

Table 5

How Each Resource Structured Presentation of Big Ideas and the Quantity Provided

Resource	Top-Level Organizational Structure	Evidence	Number of Big Ideas
P2MT	Book for the specific grade band P-2 then Domains or sometimes topics	Chapters organized by separate domains so no cross-domain connections used (i.e., *sets, number sense, counting, number operations, data analysis, spatial relationships, shape, pattern*)	26
K8MT	Strands or parts of a domain	Chapters are organized as separate strands or parts of domains so no cross-domain connections used. However, given that some domains are grade-band specific, the early grade math topics for number and operations are also organizationally separated from later grade band topics. Big ideas are listed at the beginning of each chapter for Chapters 7 through 22. Unlike the other sources analyzed, the listed big ideas were not emphasized throughout each chapter. Chapters were sometimes strands (e.g., Geometry) and sometimes part of a domain (e.g., Developing Fraction Concepts).	75
K8PD	Grade	Each book in the series is for a separate grade and the overview article separated sections by grade (i.e., K, 1, 2, 3, 4, 5, 6, 7, or 8),	80
P12PD	Grade band, then topic	Separate books by grade bands (i.e., K-2, 3-5, 6-8, 9-12) and Topic (e.g., Functions, Expressions and Equations; Rational Number; Addition and Subtraction)	>43 with >153 Essential Understandings in the 12 books of the series analyzed

Quantity of Big Ideas Obscures Coherence

Refer again to Table 5. Column 4 displays the number of big ideas found. Note that the quantity ranged from 26 big ideas stated in a resource for P-2 teachers, to 80 in a resource spanning P-8. P12PD might seem to be within this range, however, the 12 publications we analyzed were most of the series, so there are more than 43 big ideas in the resource. Moreover, unlike the other resources, the authors specified at least 153 more ideas (i.e., essential understandings) that they stated a teacher must understand in order to comprehend the big ideas themselves. In other words, the big ideas in P12PD were insufficiently independent statements to meet Charles' (2005) criteria for a big idea. Furthermore, in some publications even the "essential understandings" were also insufficiently independent statements such that even 153 is an underestimate of the number of ideas teachers must learn. For example, just one big idea about ratios, proportions, and proportional reasoning was delineated: "When two quantities are related proportionally, the ratio of one quantity to the other is invariant as the numerical values of both quantities change by the same factor (Lobato & Ellis, 2010, p. 11). However, what was labeled as a big idea was really a mathematical definition available in other mathematical texts, such as traditional mathematics textbooks. Consequently, the authors asserted: "Although the big idea of proportionality may at first seem straightforward, developing an understanding of it is a complex process for students. It involves grasping many essential understandings" (Lobato & Ellis, 2010, p. 12). Next the authors proceeded to document 10 essential understandings. Two of these, however, were also insufficient statements that had four bullet points, each of which were really the meanings teachers need. Thus, this purported single big idea was really 16 ideas.

Redundancy and Omission of Big Ideas Inhibits Vertical Alignment: The Case of Composing and Decomposing

Given that big ideas are meant to be overarching and provide coherence, big ideas stated in one grade or topic that are relevant in a later topic or grade should be clearly stated (rather than omitted) in a way that avoids redundancy or repetition. Moreover, K8PD referred to some big ideas as being "even bigger than" big, such as "composing and decomposing with numbers and shapes" (Boaler et al., 2017, p. 5). Thus, we chose this as a case. Table 6 documents each compose/decompose related idea and where this big idea appeared in each of the analyzed resources in terms of grade levels and content domains or topics.

Notice in Table 6 that only the topics of numbers and shapes are acknowledged in these resources as being supported by big ideas of compose/decompose. Also notice the limited number of grades in which even number or shapes was mentioned (see Table 6).

Table 6

Compose and Decompose Relevant Big Ideas Found in Each Resource

Resource	Domain or Topic	Grade	Compose/Decompose Relevant Big Idea (Even If Not Explicitly Stated as Such)
P2MT	Number	P-2	"A quantity can be *decomposed* into equal or unequal parts; The parts can be *composed* to form the whole" (p. v).
	Shapes	P-2	"Shapes can be combined and separated (composed and decomposed) to make new shapes" (p. vi).
K8MT	Base-Ten Number	K-2	"Flexible methods of addition and subtraction computation involve taking apart (decomposing) and combining (composing) numbers in a wide variety of ways. Most of the decomposing of numbers is based on place value or *compatible* numbers-which are number pairs that work easily together, such as 25 and 75" (p. 239).
		1-3	"Multidigit numbers can be built up or taken apart in a variety of ways to make the numbers easier to work with. These parts can be used to estimate answers in calculations rather than using the exact numbers involved. For example, 36 is the same as 30 and 6 or 25 and 10 and 1. Also, 483 can be thought of as 500 – 20 + 3" (p. 239).
K8PD	Number	K	"We can put numbers together" (p. 5).
	Shapes	2	"Partitioning shapes" (p. 6).
	Shapes	6	"Taking apart prisms & polygons" (p. 8).
P12PD	--	P-12	--

P2MT gave two big ideas about composing and decomposing, one for number and one for shapes. K8PD provided three big ideas related to composing/decomposing, one for number (Kindergarten) and two for shapes (Grades 2 and 6). P12PD did not mention composing or decomposing in their stated big ideas. These could only be found by looking at the subcategories of big ideas (i.e., *essential understandings*) and we found this only in a single domain/strand type of Geometry/Measurement in just two non-adjacent grade bands (i.e., K-2 and 6-8). Thus, in P12PD compose/decompose was not aligned vertically across grade bands with a gap between Grades 2 and 6 and then terminates prior to high school. Although K8MT is a methods textbook informing three grade bands, it provided just two composing/decomposing big ideas about base-ten numbers relevant to Grades K to 3. This base-ten number focus, however, was an important application of a compose/decompose big idea that the other resources failed to mention.

It is crucial to point out that only the methods textbooks (P2MT and K8MT) explicitly included the inverse relationship of composing *and* decomposing in each stated big idea. K8PD showed only composing *or* decomposing in any grade-level, which misses the opportunity to emphasize the relationships between putting together *and* taking apart numbers or shapes. In K8PD, we could recognize the big idea of composing/decomposing in the stated big ideas. However, the language differed in each instance (i.e., "put . . . together" in K, "partitioning" in Grade 2 and "taking apart" in Grade 6) such that the overarching connections across grades and domains may not be obvious to a teacher without further explanation.

P2MT's consistent and explicit language in more than one domain and grade would make it easier for teachers to see that this idea connects across domains/strands. Although K8MT used the term compose/decompose, the authors only addressed this big idea in two of the 75 stated big ideas and only for number. Yet, notice the redundancy that these two big ideas were offered on the same page and presented as two separate ideas (i.e., the first about "compatible numbers" and the second about "multi-digit numbers"), rather than a single concise overarching explanation of the value of composing and decomposing quantities that we can apply to calculations with a compatible number strategy or procedures with multi-digit numbers.

Discussion

One consistency we found across resources was that the audience for big ideas was teachers, not students, and the goal was to improve their knowledge for teaching or MKT (RQ1). This purpose found in our analysis was also consistent with the purposes as stated in the field (e.g., Askew, 2013; Charles, 2005; Siemon, 2022). In contrast, across analyzed resources there was inconsistency as to whether a resource stated the importance of big ideas without definition/explanation, talked around big ideas, or offered a definition (RQ2). This should not be surprising given that Askew (2013) found there was not an agreed upon definition in our field.

Almost two decades ago Charles (2005) referenced the dilemma of determining how big a big idea is and what makes an idea robust enough to be considered "big." In light of the recent proliferation of documents asserting that teachers must know "the big ideas" (e.g., NCTM, 2014), we had hoped our analysis of recent resources would provide some clarity to this dilemma. To answer RQ4 regarding the size of the big ideas, we considered what the resources said big ideas were, as well as our analysis of the actual stated big ideas. Both of these approaches revealed inconsistencies *across* resources. The explanations and definition focused to varying degrees on whether the purpose of a big idea was to connect topics, connect ideas within topics, connect big ideas to each other, or something larger (see Table 3). The analysis of the actual stated big ideas also revealed inconsistent size *within* each resource (see Figure 1). Therefore, the analysis could not offer clarity about how big a big idea is (RQ4).

A consistency across resources was that big ideas *should* organize or provide coherency for mathematics, which was consistent with prior claims (e.g., Ritchhart, 1999; Siemon, 2022). However, our analysis for RQ5 revealed that the organizational structures of each resource still used the traditional approach of grade or grade band as the top-level structure, then segmented by topic, and finally by big ideas as a third-level category. In contrast, Charles (2005) who sought content validity from colleagues for his set of big ideas, was told to avoid such artificial divisions and corrected this prior to publication. From a disciplinary perspective of mathematics, we avoid redundancy and seek parsimony. Consider how we value hierarchical categorizations of quadrilaterals to avoid redundantly restating all possible properties of each shape; we value definitions as necessary and sufficient. Yet, our analysis found redundancy and insufficient use of the selected test case of the big idea of composing/decomposing. Therefore, if a resource mentions the importance of compose/decompose for one topic or grade, then as a field we should expect the resource to include many or all instances of this big idea across topics, domains/strands, and grades. However, this was not what we found.

In spite of the composing aspect of shapes explicitly being stated beginning in the Kindergarten standards (K.G.6 *CCSSM*), neither the P-12 Professional Development Series nor the K-8 Methods Textbook included a compose/decompose big idea for shapes and only the decomposing aspect of shapes were included in the K-8 Professional Development resource (see Table 6). Moreover, all resources omitted a composing/decomposing idea about measurement in spite of how crucial the big idea of composing/decomposing is to determining areas or volumes of irregular shapes, linear measurements, elapsed time, and so forth. Identifying a big idea in one instance but omitting it from other relevant instances (grades or applicable topics), reduces the power the big idea could have in a student's mathematical career.

Given that Charles (2005) was the only document we could find that provided a theoretical perspective of big ideas in terms of a definition with criteria, it makes sense that each of the resources and much of the literature used this work as the foundation for their construct of big ideas of mathematics. Yet, as we demonstrated in the findings, Charles' criteria were inconsistently applied in every analyzed resource (RQ3). Recall that in each resource big ideas were found that were topics, questions, paragraphs, or statements that were not in themselves mathematically meaningful (see Table 4). Charles (2005) noted that when asking teachers what a big idea is, they provided ideas such as topics, strands/domains, objectives, or standards. These teacher conceptions are consistent with the variety of big idea formats we found in our analysis of resources designed to inform teachers. Thus, what teachers think big ideas are, is consistent with the resources that informed them. How could the criteria of centrality to mathematics and coherence within mathematics be achieved when 26 to 80 big ideas were given to teachers (see Table 5)? Moreover, these overwhelming quantities in some cases only reflect a narrow set of grade bands (e.g., P2MT) or require 153 additional and sometimes multi-part "essential understandings" in order to comprehend the 43 "big ideas" (P12PD, see Table 5).

Hence, to vertically and horizontally align all of mathematics would require even more ideas. Rather than making teaching easier, this expansive set of ideas, in addition to standards, would make teaching more challenging. In contrast, the foundational work of Charles, which was cited by these resources, proposed fewer big ideas than any of the analyzed resources. The way Charles accomplished this was by making the big idea the top-level of organization in two ways: 1) he avoided organizing by grade band and 2) due to colleagues' content validation feedback on a draft, he eliminated the content strand/domain as an organizing feature to instead use it as sub ideas of applications of each big idea. To be clear, each of his sub ideas provided specificity and examples to support the same core overarching idea—which is in sharp contrast to the ways the "essential understandings" with sub-bullets were distinct additional ideas (as noted in the RQ5 findings section). By eliminating this structural redundancy, Charles (2005) was able to reduce the number of stated big ideas by about a third— down to 21 for all of grades K to 8. Thus, as a field we have much work to do to clarify and organize the construct of big ideas and our communication of big ideas to teachers.

Conclusions and Implications

Many people who have invested considerable time with the construct of big ideas specifically state that a canon of agreed upon big ideas is unlikely, perhaps impossible, or even undesirable (Askew, 2013; Boaler et al., 2017; Charles, 2005). In spite of this, U.S. policy statements and documents refer to big ideas with the article "the" as though these are delineated things teachers should have learned during teacher preparation or professional development (AMTE, 2017; NCTM, 2014). To take the next step in the evolution of this construct to be a useful support for teachers, teacher educators, and scholars we offer several suggestions. Philosophically, we ask the field to approach the construct of big ideas the way Charles (2005) and Boaler et al. (2017) do by using the article "a" instead of "the." This is an especially important revision for future editions of those policy documents and pedagogy books that use the term "big ideas" without articulating what they are and often mentioned the construct as though a command to learn an existent list to which teachers should already have access. This shift in recognizing "a set" instead of "the" big ideas would soften the language in such documents to honor teachers' professionalism and better reflect scholarly humility that more accurately reflects the current state of the field that there is much that is unknown and not agreed upon.

The construct of big ideas needs guidelines that are teacher, teacher-educator, and scholar friendly. To advance, we look back to Charles (2005) and then build on his valuable theoretical perspective.

Definition and Criteria for Big Ideas

Let us begin with Charles' definition that encouraged broader connections and implications than simply connections within a topic or between topics as some analyzed resources did: "A *Big Idea* is a statement of an idea that is central to the learning of mathematics, one that links numerous mathematical understandings into a coherent whole" (Charles, 2005, p. 10). We used and extended his criteria to specify the following five criteria.

Portable and Meaningful Name Criterion

Big ideas must have a name (Charles, 2005). We agree with this naming criterion. However, we suggest better implementation of this criterion than Charles himself implemented or any of the resources we analyzed. These should be named so as to be a concept a person can own and use in varied contexts and situations. In other words, it should be portable. The name should not be a topic, because it would be insufficiently descriptive given that multiple big ideas could relate to a topic. We suggest that a shortened descriptive form of the meaning of the intended statement would be most useful. For scholars it may help to think of this as a "Running Head".

Big ideas should avoid numbering, even if named. Numbering big ideas locally as we referred to them in the findings, restricts their portability to another context. Given that several have claimed that there will not be universal agreement on which big ideas should be used (Askew, 2013, Boaler et al., 2017; Charles, 2005), then numbering them in any resource creates additional barriers and hurdles to using these within districts or at a more macro scholarship level to build knowledge as a field. Moreover, numbering connotes an ordered sequence that violates the intended purpose of promoting connections and implicitly prioritizes the first big idea as most important. Thus, naming rather than numbering is the only way they way will be useful for the lay person and most likely the only way it could be useful for teachers. Naming big ideas, however, could foster a common language about each particular big idea.

Ethical Communication Criterion

To ensure broad accessibility, the simplest lay language possible should be used (Su, 2017). To humanize mathematics as something humans created and do, active voice should be used. Active voice is also easier to understand than passive voice (Schimel, 2012).

Portable and Stand-alone Meaning Criterion

Grammatically, a big idea must be a statement and it must stand-alone. This was the intention of Charles (2005) that it must be a statement with "mathematical meaning" (p. 10) and that it must be "useful to teachers, curriculum developers, test developers, and those responsible for developing state and district standards" (Charles, 2005, p. 11). The big idea statement must convey meaning of an important idea in and of itself. This might seem obvious, however, as Table 3 revealed, each of the analyzed resources presented at least some big ideas that would need to be revised to meet this criterion.

Connection and Example Based Presentation Criterion

A big idea should be the top-level statement with applications of this idea or sub ideas organized into domain/standard and subtopics via bullets (e.g., Charles, 2005), a table, and/or a diagram (e.g., Boaler et al., 2017; Boaler & Williams, 2021). Although Charles did not explicitly state this as a criterion, he modeled this approach when he presented a set of big ideas. We believe this is important to facilitate understanding of the degree to which a big idea applies to and connects mathematical ideas.

Criterion to Categorize and Prioritize Big Ideas by their Size and Power

Big idea statements should be stated at the broadest level of implication possible that still fulfill the criterion of being a mathematically meaningful statement. "Big Ideas need to remain BIG and they need to be the anchors for most everything we do" [capitalization in the original] (Charles, 2005, p. 12). Using this mind-set to determine and state a big idea in this way would eliminate the need to create separate listings of redundant big ideas. This would create an efficient and coherent system that is more manageable for teachers, just as a hierarchical categorization of quadrilaterals or number systems promotes efficiency and coherency in the discipline of mathematics itself (De Villiers, 1994). The details of how and where this big idea applies would be clarified by adherence to the previous criterion about how to present a big idea over the applicable domains and examples.

The construct of what a "big idea" is warrants a more precise definition that indicates relative size and connective power. We see our stance to ask for more precision of this pedagogical construct as analogous to expectations of Mathematical Practice 6 (NGA & CCSSO 2010). That is, we call for more precision about the language of teaching mathematics analogous to precision of the language to do mathematics. For instance, when even very young children use the word "big," the recommendations are to encourage them to refer to specific attributes with words like taller, shorter, longer, heavier, and so forth. In favor of more precise indications of the size of an idea, let us let go of using the term "big idea" to refer to the specific statement. We primarily suggest this due to the lack of agreement on the meaning and size of "big" ideas as well as the issue that many other content areas and pedagogical approaches, such as the International Baccalaureate (2023), use the term "big ideas" in much broader and different ways. We also saw this in instructor responses to the big ideas of secondary methods courses (Stehr et al., 2019). For these reasons the vague and relativistic connotation of "big" would continue to perpetuate confusion among teachers and scholars alike.

Thus, we suggest sets of ideas or the construct can continue to be referred to as "big ideas," however, we advocate for more precise terms about the sizes of big ideas.

Not all big ideas are equally important or central to the learning of mathematics. Clarifying the size of a big idea by the quantity and type of connections will help the field to (1) reduce the number of big ideas expected of teachers and (2) prioritize big idea instruction based on the differing contexts of P-12 classroom learning or teacher education. This would be consistent with the intended purpose of big ideas (Askew, 2013; Hurst, 2014; Siemon, 2022). To this end we next offer the Big Ideas Framework.

Big Ideas Framework

To categorize and prioritize big ideas by their size and power we developed the Big Ideas Framework shown in Table 7.

Table 7

Big Ideas Framework

Name	Size/Applicability Description	Examples
Mighty Mega Math Ideas	Overarching idea *across* **domains/strands**: An idea that spans grades and **unites domains/strands** to em**power** students to look for these ideas in any new concept to **succeed in the discipline of mathematics**. Consistent use of these should potentially be high-leverage practices.	*Compose & Decompose*: We can look for ways to put together and take apart things in math to solve situations.
Power Math Ideas	Overarching idea *within* a **domain/strand**: Spans grades and **unites topics** to em**power** students to succeed in a domain/strand.	*Purpose of Measuring*: We measure to compare the same attribute of two or more objects or groups of data. *How We Classify Shapes*: We identify and classify shapes by their properties.
Strong Math Ideas	Overarching idea *within* a **topic**: Spans grades within a topic to **strengthen** student understanding of a topic.	*How We Write and Think in Base-Ten*: Our number system uses a base of ten, so we use the digits 0 to 9 to write numbers and think in groups of ten (and groups inside groups inside groups…) in special ways so that each bigger or smaller group is a unit with a special name.

Each of these ordinal levels span grades to ensure vertical alignment, which is consistent with prior assertions (Boaler et al., 2017; Charles, 2005; Small, 2019). Further, to be sufficiently central to mathematics we intend that spanning grades also means bridging across grade band(s), consistent with AMTE (2017).

The framework consists of three ordinal levels: Mighty Mega Math Ideas, Power Math Ideas, and Strong Math Ideas. Note that we used the word "math" to reinforce the content area of mathematics within the name of each level. Metaphorically taking the perspective of the ideas, the levels are shown in decreasing order beginning with the greatest power as in it takes greater power to span or connect across a gap, so thinking of ideas that connect across larger barriers as needing to be stronger. From the perspective of the students, these levels have varied strength in the degree to which they might empower students to succeed based on the quantity of ideas that a level could support.

Boaler et al. (2017) stated that "As we wrote these big ideas, it was clear to us that there are some even bigger ideas that pervade all of mathematics" (p. 5). Charles (2005) explained that "many" big ideas span strands, which implies that not all big ideas are that big. Hence, we specified those ideas that empower students in all of mathematics both vertically and horizontally by spanning multiple strands/domains as Mighty Mega Math Ideas. Those ideas that span topics within domains or strands are Power Math Ideas, which is the level consistent with a "generative idea" from the strand of measurement that teachers working with Ritchhart (1999) determined.

The four ideas we selected as examples to illustrate each level in Column 3 of Table 7 have their roots in prior work: *Compose & Decompose* (Boaler et al., 2017; Clarke et a al., 2012; Early Learning Collaborative, 2014; Van de Walle et al., 2019); *How We Classify Shapes* (Charles, 2005; Early Learning Collaborative, 2014; Van de Walle et al., 2019); *Purpose of Measuring* (Kader & Jacobbe, 2013; Ritchhart, 1999; Van de Walle et al., 2019); and *How We Write and Think in Base-Ten*, (Boaler et al., 2017; Charles, 2005; Van de Walle et al., 2019; Yumi Deadly Mathematics, 2016). Each of which we revised in Table 7 to adhere to the five criteria we set forth in this section.

Notice that we did not restrict Compose & Decompose to numbers and shapes as the analyzed resources did. Compose & Decompose should be one of the high-leverage ideas to prioritize and organize instruction across all domains due to its horizontal and vertical strength. How much power or leverage could this Mighty Mega Math Idea lift? Compose & Decompose, if prioritized, would empower students and teachers to make connections and provide coherence within grade levels, which initial analyses in other in-progress work we found applied to at least 29% of kindergarten standards, 43% of grade one standards, 37% of grade two, 30% of grade three, 32% grade 4, 18% grade 5, 10% in grade 6, and 30% in grade 7. For example, standard 6.G.1 includes the exact phrase of "composing . . . decomposing," whereas 6.G.4 (NGA & CCSSO 2010) does not contain this language nor synonyms. Yet to succeed on this standard about finding surface areas students need to use a composing and decomposing conception of mathematics. In subsequent grades Compose & Decompose is relevant to some standards (albeit with lower impact percentages as the content to be learned emphasizes more proportional reasoning while continuing to require additive reasoning in the problems they solve). Moreover, the purpose is that a Mighty Mega Math Idea would empower students as they move through grades and learn new domains such that even these large within grade-level percentages underestimate the long-term cumulative vertical power of this Mighty Mega Math Idea.

Purpose of Measuring (Ritchhart, 1999) and *How We Classify Shapes* (Charles, 2005; Early Learning Collaborative, 2014; Van de Walle et al., 2019) are central to mathematical ideas and metaphorical heavy lifters within the strands of Measurement and Geometry, respectively. Thus, they are needed to empower students to succeed in these strands. Yet, given that they are only applicable to a single strand, they cannot be as central to mathematics as any other such idea that teachers or scholars determine applies across multiple strands/domains and grade bands. Nevertheless, the *Purpose of Measuring* is a Power Math Idea that could empower citizens to understand the utility of measuring beyond accurate procedures of measuring—the larger purpose of why we measure, what we measure and how to make decisions about measuring is important for physical measurements (Ritchhart, 1999) as well as data. This is the reason the *CCSSM* (NGA Center & CCSSO, 2010) domain connects data and measurement. Moreover, *How We Classify Shapes* could go a long way toward correcting the misconceptions that shapes are classified by memorizing an image or a template, which adults and children harbor (Fujita, 2012; Nurnberger-Haag et al., 2020; Nurnberger-Haag et al., 2021; Ozdemir Erdogan & Dur, 2014). Furthermore, imagine the impact on student learning if this Power Math Idea— that shapes are classified by their properties— was reinforced while following the Property-Based Shape Sequence (Nurnberger-Haag & Thompson, 2022).

Although weaker in its centrality to mathematics overall, disciplinary knowledge cannot be strong without a strongly connected understanding of any given topic. Strong Math Ideas promote this connectivity within a topic that standards implicitly fail to impart due to aspects of topics being separated into different grades and often further separated into discrete bits of knowledge. Indeed, this conceptual understanding or bigger picture of the base-ten number system conveyed in our wording of the Strong Math Idea *How We Write and Think in Base-Ten* communicates essential patterns and concepts of the base-ten number system that are almost non-existent for students and teachers who focus on incrementally building up discrete place value and calculation skills in each grade. This Strong Math Idea would be an important guidepost for students and teachers from the beginning of base-ten number instruction. Rather than *trading*, *bundling* or *regrouping*, thinking of the number system as successive sets that *contain* ten is crucial to a strong sense of number (see Nurnberger-Haag, 2018). Thus, we see Strong Math Ideas as the smallest level of the big ideas construct, yet whose strength is necessary to ensure understanding a topic.

Prior authors have included the idea of power in their thinking about big ideas of mathematics (e.g., Boaler et al., 2017; Carnine, 1997; Tout et al., 2015). However, the idea of power has not appeared in a definition, criteria, or denotation of the size of big ideas. Previously relative size of big ideas was either not attended to, which implied all big ideas were of equal size, or vague indications of size were offered (see section Are Big Ideas Consistently Big?). Whereas we emphasize this power-based connotation of the reason to use big ideas in the definition at each level to denote the relative size within each level of the Big Ideas Framework.

Shift from MKT to CCK

Some frameworks should remain pedagogical guidelines that influence instruction but are never taught to P-12 students. For example, the van Hiele Framework of Geometric Reasoning is important for teachers to understand how to better teach geometry (van Hiele, 1986). It would not make sense, however, to teach children the van Hiele levels even though the goal is to help students progress *through* these levels. The van Hiele levels framework is an example of Mathematical Knowledge for Teaching (MKT; Ball et al. , 2008; Nurnberger-Haag et al., 2021). In the literature cited as well as the resources we analyzed, big ideas were developed for and continue to be intended as MKT.

We argue that big ideas of math need to be Common Content Knowledge. We propose a fundamental shift from the construct of big ideas being theoretically perceived as an aspect of MKT to being understood and implemented as an aspect of Common Content Knowledge. Big ideas are so important that they are crucial to helping students and families understand mathematics as a coherent and logical discipline. Our intention is that from one grade to the next, if students themselves own the most expansive and powerful ideas (i.e., Mighty Mega Math Ideas) as part of their Common Content Knowledge and have been taught to look for these in new topics, even if in a subsequent grade they have a teacher who does not foster these connections, the students could independently feel empowered to do so. In other words, students could have greater agency as mathematical thinkers. Imagine schools where Mighty Mega Math Ideas were posted on classroom and hallway walls (i.e., as an element of environmental math; Nurnberger-Haag et al., 2019). What if these ideas were also shared with families in other ways to destigmatize math, help families feel the power of math, and recognize that it was the disconnected way they were taught that may have fostered math anxiety, not mathematics itself. This could help students and families feel that mathematics makes sense and envision futures that include using math. Studies should investigate these longitudinal hypotheses. If students, themselves, truly own the Mighty Mega Math Idea of Compose & Decompose, for instance, in the U.S. it would support about one-fourth of their K-8 standards (287 standards with at least 70 related to composing and decomposing) as being interconnected and coherent. Imagine if just a few other Mighty Mega Math Ideas were similarly prioritized. Most sources espouse the goal to have students see mathematics in this connected way, which will not happen if big ideas remain hidden as the pedagogy of the teachers. Thus, we adjusted Charles' (2005) definition of a big idea by changing the phrase "central to *the learning of* mathematics" (p. 10) to "central to *understanding* mathematics."

Summary and Future Directions for Big Ideas of Mathematics

Individual studies, constructs, and areas of research in mathematics education must use theoretical framing (Leatham, 2019; Spangler & Williams, 2019). Mathematics education values explicit theoretical frameworks that can be used as analytic frameworks to create a shared language for constructs, provide frames to recognize which aspects of a construct might be the focus of research questions, delineate initial codes for analysis, and build shared understanding through multiple studies reporting about the same phenomenon (Spangler & Williams, 2019). Yet, as others had noted there has been a lack of shared language or meaning related to big ideas (Askew, 2013; Siemon, 2022), which our study confirmed. That is, big ideas were a construct in need of a framework. As Boaler et al. (2017) noted, the big ideas construct "will evolve with our thinking" (p. 5). Thus, we suggested next steps in the evolution of the theoretical framing of the big ideas construct to foster the impact upon which the field has agreed: to help students see mathematics as an interconnected and coherent whole (Askew, 2013; Boaler et al., 2017; Tout et al., 2015).

Just as it is easier for students to learn accurate mathematics the first time it is introduced, rather than to correct or clarify terms later (NRC, 1989; Nurnberger-Haag et al., 2021), in the U.S. it will likely take teacher educators and teachers longer to clarify and advance the big ideas construct than countries where mathematics teacher educators and scholars could use the following seven recommendations to break ground to build a strong foundation from the beginning. The first suggestion is to use our revised definition that is essentially Charles' (2005) definition but with the crucial shift to Common Content Knowledge: "A big idea of mathematics is a statement that is central to understanding mathematics, one that links numerous mathematical understandings into a coherent whole." Second, to foster vertical and horizontal alignment, use the Big Ideas Framework consisting of three ordinal levels that span grades as well as grade bands: Mighty Mega Math Ideas (unite domains/strands), Power Math Ideas (unite topics within a domain/strand), and Strong Math Ideas (unite ideas within a topic). Third, when selecting or using ideas in any of these levels, use the five criteria summarized in the bullets below.

- Portable and Meaningful Name
- Ethical Communication
- Portable and Stand-alone Statement
- Connection and Example Based Presentation
- Categorize and Prioritize Big Ideas by their Size and Power

Fourth, instruct P-12 students and families on selected ideas to develop a society that can see the roots though the leaves when so many mathematical ideas and topics have become camouflaged due to language that obfuscates the underlying ideas that unite them. At a minimum, Mighty Mega Math Ideas would be beneficial candidates to prioritize for vertical alignment within school districts from preschool through Grade 12. Fifth, organize mathematics teacher education courses around a few Mighty Mega Math Ideas and Power Ideas. As mathematics teacher educators we already have such limited course time that we cannot cover every standard for every grade during our methods or content courses, so we already make difficult choices about what to cover. Using the two most powerful levels of big ideas to organize instruction should be a high-leverage practice way of making such choices. Sixth, although, many have advocated organizing instruction around big ideas (Bruner, 1960; Charles, 2005; Ritchhart, 1999; Siemon, 2022), our analysis revealed that resources have yet to be structured in this way. New resources as well as the next editions of existing books about big ideas could use these recommendations to reduce, reorganize, and structure big ideas as the top level in light of the five criteria and the framework.

Finally, we were disheartened that given the growing popularity of the construct, what Kuntze and colleagues (2011b) lamented is still true a decade later: "empirical research on professional knowledge connected with big ideas in mathematics is scarce" (p. 2717). Moreover, we have yet to find peer-reviewed research publications that empirically test the impact of using big ideas. Given how adamantly policy documents in the U.S. and numerous authors have claimed that big ideas are crucial teacher knowledge, as do we from our own practice, such claims have yet to be substantiated with research. As a field of mathematics education scholars, we can do better. The Big Ideas Framework provides three levels of big ideas to focus research designs, specify what was investigated, and communicate results in a way that studies could build upon each other, consistent with the purpose of a framework in mathematics education (e.g., Spangler & Williams, 2019). Research should investigate how using particular levels of big ideas impacts teacher knowledge and P-12 students' performance on the traditionally accepted aspects of Common Content Knowledge as well as their perception of mathematics as a discipline of coherent and interconnected concepts.

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Developing K-12 Teachers' Actionable Understanding of the Multidimensional Next Generation Science Standards

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ABSTRACT

This study explored K-12 teachers' understanding and implementation of the Next Generation Science Standards (NGSS) during and after participation in a professional development (PD) program that included the development of science teachers' conceptual understanding of science. We add to the literature with our focus on a multi-year PD program emphasizing the vertical progression of concept development from kindergarten to 12th grade, rich engagement in science and engineering practices and crosscutting concepts, deep understanding of NGSS, and collaborative discussion to develop research-based pedagogical strategies to teach the three dimensions. In particular, we focus on foregrounding/backgrounding dimensions throughout a science unit to simplify instruction. Through an exploratory qualitative approach, we sought to answer the following research question: *During a three-year professional development program, how do K-12 teachers develop an actionable understanding of the intertwining three dimensions of the Next Generation Science Standards?* Teachers participating in all three years of the project were involved in school-based focus group interviews to elicit their understanding and implementation of the NGSS, especially regarding the interweaving nature of the three dimensions of the NGSS. Findings suggested that although the standards are complex, it is critical to be explicit about the three dimensions and intentional about planning for instruction. Collaboration in vertical teams and deep reflection on content and pedagogy were essential elements of the PD program. This study offers insight into the time it may take for individuals to substantially shift their daily teaching practices, underscoring the complexity of the standards and teaching shift we are asking of our teachers. Thus, foregrounding/backgrounding the dimensions throughout a unit may support teachers' actionable understanding of NGSS.

Keywords: NGSS, multi-year professional development, vertical teaming

Introduction

A Framework for K-12 Science Education (National Research Council [NRC], 2012) and the ensuing Next Generation Science Standards ([NGSS], NGSS Lead States, 2013) form the foundation of a rich vision for K-12 science teaching and learning. This framing includes science concepts, practices, and theoretical underpinnings of the development of scientific knowledge. The developers of the NGSS considered the skills needed for science education in the 21st Century, aimed to improve scientific literacy, and endeavored to create standards that lead to student understanding of big science concepts. The current framing includes three intertwining dimensions: disciplinary core ideas (DCIs), science and engineering practices (SEPs), and crosscutting concepts (CCCs).

Research suggests that teachers need professional development (PD) to support their understanding of this reform-based science teaching (Smith & Nadelson, 2017). The complexity of the NGSS results in a need for rich PD experiences—indeed, the framing of the standards presents a shift from the foci of previous standards (Nollmeyer & Bangert, 2017; Pruitt, 2014). Previous studies have examined the results of PD for teachers that focused on the new framing of the standards. Findings include the complexity of the standards posing a unique challenge (Smith & Nadelson, 2017) and how rich coaching and support can increase teachers' engagement in reform-based science teaching (Berg & Mensah, 2014).

The current study explored K-12 teachers' understanding and implementation of the NGSS during and after participating in a PD program that included the development of science teachers' conceptual understanding of science, focusing on areas within the NGSS not included in previous state standards. We add to the literature with a multi-year PD program emphasizing vertical teaming and concept development from kindergarten (K) to 12th grade, rich engagement in SEPs and CCCs, deep understanding of the NGSS, and collaborative discussion to develop research-based pedagogical strategies to teach the three dimensions. Through an exploratory qualitative approach, we sought to answer the following research question:

> During a three-year professional development program, how do K-12 teachers develop an actionable understanding of the intertwining three dimensions of the NGSS?

Conceptual Framework and Guiding Literature

Similar to the work of Nollmeyer and Bangert (2017), the NGSS framework guided the conceptual development of this study. Moreover, the crux of the current study was how the three dimensions intertwine and the theoretical underpinnings of how this is presented within *A Framework for K-12 Science Education* ([henceforth called *Framework*], NRC, 2012).

Next Generation Science Standards

The overarching goals of the NGSS involve teaching students in more authentic ways—to engage students in "doing" science rather than simply "knowing" science. The innovations in the NGSS require science educators to use new approaches in teaching (Bybee, 2015; Reiser, 2013; Stiles et al., 2017) and to shift their instruction to focus on multidimensional learning experiences (Hoeg & Bencze, 2017). The *Framework* (NRC, 2012) and the NGSS include learning progressions that begin in the elementary grades and continue through high school graduation. Unlike past science standards, the NGSS performance expectations require students to deeply understand DCIs, demonstrate the ability to show evidence of knowledge through SEPs, and connect CCCs across disciplines (Pruitt, 2014). The NGSS are guided by performance expectations that elucidate how the three dimensions can be intertwined, reflecting a view of what it means to learn science (Penuel et al., 2014). The performance expectations are essential to the NGSS because the three dimensions work together to build an integrated understanding of a rich network of connected ideas (Krajcik et al., 2014). The NGSS call for a seamless interweaving of the three dimensions, including developing scientific knowledge (SEPs) and the thought processes that allow for connections across science disciplines (CCCs). Lederman and Lederman (2013) pointed out that the NGSS are more comprehensive than previous reform documents because of their multidimensional focus. Students should demonstrate knowledge in use (NRC, 2012) and develop the ability to use scientific concepts, problem-solve, think critically, and make statements based on evidence when all three dimensions are interwoven (Krajcik et al., 2014). Furthermore, meeting performance expectations includes developing an integrated understanding of science as a body of knowledge and a set of practices and applying CCCs to deepen understanding of core ideas (Penuel et al., 2014).

Due to the complex nature of the NGSS, we anticipated that teachers would need structured support on how to understand, unpack, and implement them. Indeed, previous studies have found that teachers needed PD on various aspects of the standards (Haag & Megowan, 2015) as they have struggled to conceptualize the three dimensions (Smith & Nadelson, 2017). We thus explored how a rich PD program that focused on the multidimensionality of the standards across grades K-12 could transform into the planning of actionable teaching moves in classrooms, shifting from work with standards that focus on discrete facts to emphasizing more significant complex concepts (Pruitt, 2014).

The interweaving of the three dimensions of the NGSS is analogous to the strands of a rope (Krajcik et al., 2014). A strong rope forms when each strand is present and intertwined within science instruction. All three dimensions must be integrated; otherwise, a strand is missing, and the rope is weakened. This shift in reform-based teaching requires an actionable understanding of how the three dimensions work together to strengthen the "strands of rope" in science education.

Pruitt (2014) identified the importance of instructional planning of an entire unit with the three dimensions in mind, resulting in a coherent learning experience for students. On the contrary, a day-to-day planning approach would negate coherence. This might lead students to believe that science concepts could be more cohesive—missing the bigger picture that many concepts and skills in science are present across disciplines. Because of the complexity of the NGSS, it is vital to focus teachers' learning within the context of their classrooms (Stiles et al., 2017). Additionally, researchers identified the need for action to aid in the transition from adoption to implementation of the standards that interweave the three dimensions of the NGSS. To overcome this challenge, PD planning and resources targeting teachers could be a key component to successfully implementing the standards, advancing this new vision of science education (Sinapuelas et al., 2019). Lee et al. (2014) and Pruitt (2014) suggested that shifting from more conventional teaching practices to the practices needed to teach the NGSS effectively requires rich PD opportunities for science teachers.

Prior research on PD related to NGSS suggests the critical importance of engaging teachers in rich experiences to understand the complex nature of the framing of the standards. Indeed, while the studies reviewed explored vital aspects of PD for teachers related to NGSS, additional information is needed to better understand the needs of teachers as they delve into the complexity of the science framework.

Professional Development (PD)

Professional development (PD) is any formal activity to support teachers' further development of conceptual understanding and pedagogical skills (Desimone et al., 2002; Quint, 2012; Whitworth & Chiu, 2015). Lederman and Lederman (2013) attributed the challenges in enacting science reform efforts to insufficient support provided to teachers in the form of quality PD. Seminal research has identified the features of effective PD. If teachers are actively involved in their learning during PD programming, just as students are while in the classroom, they will develop a deeper understanding of successful learner-centered teaching (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; Loucks-Horsley & Matsumoto, 1999). Desimone (2009) proposed a framework for teacher PD that includes content focus, active learning, coherence, duration, and collective participation. Furthermore, Richardson (2003) outlined several features in the literature needed to impact teachers positively. These include a) long-term programming with follow-up (Garet et al., 2001; Luft, 2001; National Academy of Sciences [NAS], 1996; NRC, 1996; Supovitz & Turner, 2000); b) encouraging collegiality

(Jeanpierre et al., 2005; Lieberman, 1995; Loucks-Horsley et al., 1998); c) a supportive school administration (NAS, 1996; Supovitz & Turner, 2000); d) acknowledging participants' existing beliefs and practices (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; NRC, 1996); e) agreement among participants on goals and vision (Garet et al., 2001; NAS, 1996); and f) and facilitation of the PD by an outside facilitator/developer (Bell & Odom, 2012; NAS, 1996). This list of criteria provides a strong starting point for developing a PD program.

Additional research in the field has identified the following as necessary for the creation of an effective PD experience: a) academic content (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; Jeanpierre et al., 2005; Loucks-Horsley et al., 1998); b) a well-defined image of effective classroom instruction and modeling strategies (Loucks-Horsley et al., 1998; Marek & Methaven, 1991); and c) a hands-on component (Darling- Hammond & McLaughlin, 1995; Garet et al., 2001; Loucks-Horsley & Matsumoto, 1999). Furthermore, research has identified that participants value a PD program that increases conceptual understanding (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; Loucks-Horsley et al., 1998). Jeanpierre et al. (2005) stated, "providing teachers with rich content and numerous opportunities to experience the learning that they are expected to facilitate with students may serve to assist them in translating inquiry practices to their own classrooms" (p. 686).

A need exists for PD on the NGSS (Hoeg & Bencze, 2017; Lee et al., 2014; Pruitt, 2014; Stiles et al., 2017). The NGSS's complexity requires teachers to have a rich conceptual understanding of the DCIs while using appropriate strategies to make a "strong rope" for students to learn and be able to do science, thus interweaving the SEPs and CCCs. Bell and Odom (2012) and Supovitz and Turner (2000) supported this notion. These authors stated that a goal of PD should be to support the development of knowledge of both content and pedagogy to teach science using the three dimensions of the NGSS for a more authentic learning experience for students. A high-quality PD opportunity should be designed to accomplish one or more of the following goals: assist teachers in understanding the structure of the NGSS, increase pedagogical content knowledge (PCK), and/or improve teaching strategies that will strengthen the overall science experience for learners (Penuel et al., 2014).

Prior research has suggested the value of multi-year PD for science teachers, particularly related to the reforms outlined in the *Framework*. While not surprising, research has shown a positive relationship between the number of PD hours and students' science test scores (Shymansky et al., 2012). Longhurst et al. (2016) found that eighth-grade teachers who participated in a two-year PD program learned more than their one-year and non-participating peers about science reforms, integrating technology in their teaching after participating in a two-year PD program. In their five-year PD program, Shymansky et al. (2013) focused on science content, inquiry, and integrating science with literacy. These authors found that grades three and six test scores were higher than those of comparative schools. Indeed, Rinke et al. (2018) noted previous literature demonstrating that one year of PD did not suffice in impacting teaching practice and that orientations toward professional growth and collaboration were key factors that influenced the effect of science teacher PD.

One way to support collaboration is through vertical teaming or opportunities to work with teachers across grades K-12, as it can be a powerful component of PD. Vertical teaming can support deeper engagement in the content, especially when teachers experience the content as learners and in authentic contexts (Suh & Seshaiyer, 2015; Trabona et al., 2019). Gunning et al. (2020) explored K-12 vertical teaming in NGSS PD through professional learning communities. These authors found that opportunities to work across grade levels deepened in-service teachers' views of the content and the learning progression of concepts they teach. Furthermore, teachers gained a more comprehensive understanding of the purpose and context of the concepts at their grade level. Suh and Seshaiyer (2015) explored vertical teaming in PD with elementary and middle school teachers focused on reform-based mathematics teaching. Critically, the teachers in their study developed a strong conceptual and pedagogical understanding of the tasks in which they engaged, exploring common alternative conceptions and expectations for each grade level

Our research used previous understandings of effective PD to examine how a three-year PD project influenced K-12 teachers' actionable understandings of the three interweaving dimensions of the NGSS. We contribute to this research base by focusing on three critical elements of NGSS PD: learning progressions from K-12th grades, multi-year engagement with teachers, and collaborative discussion to develop research-based pedagogical strategies to teach science using the three dimensions. Critically, we do so by emphasizing the foreground/background instructional approach (Bybee, 2013) to help teachers manage the complex nature of the NGSS.

Methods

We used a qualitative, exploratory design following what Merriam (2009) describes as one that "uncovers[s] and interprets[s]…how meaning is constructed, [and] how people make sense of their lives and their worlds" (p. 24). We explored how teachers learned about and understood the complexity and multidimensionality of the NGSS and how that learning helped inform and shape their practice through a multi-year and vertical teaming PD experience.

Participants

The district science coordinator, an active member of the PD team, invited expressions of interest in the project from teachers at schools that served large percentages of low-income students (i.e., most of the schools in the district). One condition for the study was participation as a group—at least two teachers from the same school in a common professional learning community team. Because these logistics were somewhat intensive in time and the number of busy professionals to engage (three-year time span, multiple teachers in the same school), the project included 11 schools that committed to participation. In Year One, teams of teachers (between two to four per school) from the 11 schools participated: two high schools (five teachers), four middle schools (12 teachers), and five elementary schools (15 teachers). See Table 1 for this information.

Table 1

Overview of Participating Schools (2021-22 Data, from District Website)

School ID	Student Population	School Rating: Red (lowest), Orange, Yellow, Green, Blue (highest)	Economically Disadvantaged	Student Demographics
1	1352	Orange	77.1%	47.8% Caucasian 26.1% Hispanic/Latino 19.3% African American 6.8% Other
2	2330	Red	76.0%	31.5% Caucasian 24.2% Hispanic/Latino 36.4% African American 7.9% Other
3	979	Green	45.7%	35.4% Caucasian 27% Hispanic/Latino 26.6% African American 11% Other
4	502	Yellow	57.2%	78.5% Caucasian 8.4% Hispanic/Latino 6% Two or more races 7.1% Other

Table 1 *continued*

School ID	Student Population	School Rating: Red (lowest), Orange, Yellow, Green, Blue (highest)	Economically Disadvantaged	Student Demographics
5	1289	Green	51.8%	46.6% Caucasian 8.8% Hispanic/Latino 31.5% African American 13.1% Other
6	989	Orange	71.2%	40% Caucasian 12% Hispanic/Latino 36.9% African American 11.1% Other
7	446	Orange	76.5%	23.1% Caucasian 33% Hispanic/Latino 32.3% African American 11.6% Other
8	514	Red	85.2%	9.9% Caucasian 33.7% Hispanic/Latino 46.9% African American 9.5% Other
9	299	Red	90.6%	5.4% Hispanic/Latino 86% African American 4.7% Two or more 3.9% Other
10	410	Red	85.9%	13.7% Caucasian 29.5% Hispanic/Latino 48% African American 8.8% Other
11	313	Orange	74.8%	18.5% Caucasian 18.5% Hispanic/Latino 48.9% African American 14.1% Other

As noted at the end of this section, the district also incorporated expertise and lessons learned into their district-level efforts to disseminate project-influenced resources to all schools in the district.

In some cases, school teams included a science coach who worked with the teachers at their school. The science coaches were based at each school site and were responsible for supporting teachers in the planning and instruction of science units and lessons. The level of teaching experience of participants ranged from novice teachers (1-3 years) to veteran teachers (20+ years). The schools generally had below-average academic performance in the district, and teachers seemed enthusiastic to participate in the project.

In Year One, all participants engaged in the same PD experiences that focused on the three dimensions through inquiry-based experiences about the architecture of the NGSS, the science concepts in the NGSS, and pedagogical strategies for teaching using the NGSS. In Year Two, one high school (three teachers), three middle schools (seven teachers), and five elementary schools (nine teachers) continued participation. For Year Three, based on the request by the high school teachers who indicated that they felt like they had gotten what they needed from the project, the project refocused on only elementary (six schools; 16 teachers) and middle schools (two schools, eight teachers). Approximately one-third of these Year Three teachers were new to the project due to shifts in teaching assignment grade levels and schools. These changes, driven by teacher participant requests, allowed the project to focus more strongly in Year Three on additional support for pedagogical strategies and related content knowledge deepening.

Furthermore, elementary and middle school participants requested a focus on concepts with which the high school teachers expressed that they were already comfortable. Because the project's first two years significantly focused on the vertical teaming and the learning progression of the standards, this change to include only elementary and middle teachers in Year Three did not substantially impact the overall project goal of emphasizing vertical alignment. See Table 2 for more information on the PD components.

Table 2

Connection between PD Program and Literature

Connection to Literature	PD Component
Active learning/hands-on (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; Loucks-Horsley & Matsumoto, 1999)	Teachers experienced inquiry-based activities related to DCIs, SEPs, and CCCs in NGSS (e.g., teachers created a "human wave" to model amplitude and frequency, and energy transfer)
Increase content knowledge (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; Jeanpierre et al., 2005; Loucks-Horsley & Matsumoto, 1999)	PD experiences focused on DCIs, SEPs, and CCCs that were challenging and not included in previous standards (e.g., waves, Energy, particle-level modeling of matter)
Bridge the gap between PCK and pedagogy (Bell & Odom, 2012; Supovitz & Turner; 2000)	PD included examination of student work and work in professional learning communities to collaboratively discuss science teaching and learning
Long-term follow up (Garet et al., 2001; Luft, 2001; NAS, 1996; NRC, 1996; Supovitz & Turner; 2000)	The PD program was three years long; science coaches were instructed to share ideas and concepts with teachers not involved in the project
Collegiality (Jeanpierre et al., 2005; Lieberman, 1995; Loucks-Horsley et al., 1998)	Teachers sat in school groups and vertical (K-12) teams; teachers worked in mixed-grade groups during hands-on inquiry to get to know one another and build knowledge of NGSS learning progressions
Supportive administration (NAS, 1996; Supovitz & Turner, 2000)	District specialists led the PD, and district and school administration supported the PD program
Acknowledgment of participants' existing beliefs and practices (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; NRC, 1996)	Formative assessment probes (Keeley, 2008) supported assessment and modeling of content knowledge and teaching practices; PD included discussion of existing practices that could be tuned to more tightly align with NGSS, rather than suggesting teachers needed to start from scratch
Academic content (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; Jeanpierre et al., 2005; Loucks-Horsley et al., 1998)	PD focused on DCIs that were new or particularly challenging for teachers. These were selected based on teachers' stated needs
Teaching and modeling of strategies (Loucks-Horsley et al., 1998; Marek & Methaven, 1991)	Teachers experienced inquiry-based activities related to DCIs, SEPs, and CCCs in NGSS (e.g., teachers created models of particle-level behavior of matter, including energy considerations)

By the third year, teachers expressed (and the PD team agreed) that they had appreciated the inclusion of vertical teaming work earlier in the project and found it valuable, but the elementary and middle teachers would benefit best from a more exclusive focus on content and pedagogy in their respective grade levels. In the transition from Year Two to Year Three of the project, four of the school-based science coaches were moved to the district offices to work on writing units that adapted the district science curriculum to align with the NGSS and to support teachers at schools across the district. These four district-level individuals continued to participate in the PD.

Professional Development Experiences

The PD experiences were strategically planned to enhance teachers' conceptual understanding of science, to teach how the standards progress vertically from K-12, and to address how the three dimensions of the NGSS interweave. Furthermore, the experiences were designed to support teachers' planning of intertwined three-dimensional instruction (see Table 2 for connections between components of the PD program and previous literature).

The PD team consisted of the district science coordinator, an elementary district specialist, two university chemistry professors, a secondary science education professor (Tom, third author), and an elementary science education assistant professor (Ingrid, first author). A high school science coach also participated in some of the team's planning sessions. The CCC of Energy was the overarching theme of the entire project, embedded throughout all the PD experiences. The PD also incorporated content (DCIs), SEPs, and other CCCs. All of these were discussed within the broader concept of Energy. Please see Tables 3 and 4 for descriptions of typical PD activities and an overall summary of the PD timeline and foci.

Table 3

Typical PD Activities and Differentiation Structures to Meet Teacher Needs

Typical PD Activities	Differentiation for Teacher Needs
Lived 3-D experience as a learner (e.g., modeling waves in multiple ways and articulating energy relationships to amplitude and frequency)	Heterogeneous groups (elementary, middle, and high school teachers) with 'as needed' input, questions, and responses from PD leadership team at group level for easy and frequent access
Unpacking the lived experience (e.g., identifying multidimensionality, articulating pedagogical strategies incorporated, considering how to modify or focus for different ages or abilities of learners)	Grade-alike groups. This was especially helpful for the pedagogical group-level conversations and discussions for modifying for different ages or abilities or prior knowledge of students. A PD leader participated with each group
Examining learning progression of standards (e.g., how concepts build in sophistication as students get older, how one might review to reinforce presumed previous learning and link new learning to prior)	Heterogeneous groups (elementary, middle, high school teachers). Within-group conversations of likely student uptake of concepts, likely needs to reinforce (or teach) prior learning, leveraging SEPs and CCCs over years of schooling
Planning to implement near-future lessons (DCI target of lesson to be determined by teachers according to their curriculum)	School-based PLC groups, including, when available, the school-based science coaches. Incorporated existing curriculum materials (e.g., FOSS kits) when available
Examining student work (teachers bringing samples of student work from prior cycle implementation)	Combination of grade-alike and heterogeneous groups. Grade-alike to synthesize and summarize student work, then sharing in heterogeneous groups so teachers get a snapshot of student thinking in adjacent grade bands

Table 4

Summary of PD Timeline and Foci

Year	Month	Activities
1	April	2-day PD on formative assessment
1	June	Online support through the district system: Posting of lesson plans and student work, question and answer with project leaders
1	October	Two 1-day PD sessions: 1) Focused on science content related to fields, professional learning communities, scientific argumentation, and examining student work; 2) Revisited concept of fields, focused on professional learning communities and systems and system models
2	February	Two 1-day PD sessions: 1) Focused on science content related to fields, professional learning communities, scientific argumentation, and examining student work; 2) Revisited concept of fields, focused on professional learning communities and systems and system models
2	June	Online support through the district system: Posting of lesson plans and student work, question and answer with project leaders
2	June	5-day PD on waves, models, and digital communication systems
2	August	Series of two 1-day PD sessions targeting: 1) Sharing and interpreting student work on common topics planned at the prior session; 2) Science content of matter and Energy at particle level as well as magnetism; 3) Crafting arguments from evidence; 4) Designing and conducting investigations
3	May	Series of two 1-day PD sessions targeting: 1) Sharing and interpreting student work on common topics planned at the prior session; 2) Science content of matter and Energy at particle level as well as magnetism; 3) Crafting arguments from evidence; 4) Designing and conducting investigations
3	June	5-day PD on states of matter integrated with energy considerations and practice of developing and using models

Professional learning communities ([PLC], Dufour, 2004) were implemented in Year One. Project participants engaged in three PLC cycles throughout the school year with either their school-based team or the same grade band teachers. These consisted of planning a standards-based lesson, teaching the lesson, and collaborative reflection on the lesson through analysis of student work. Participants were instructed to focus on one of three topics for each cycle: Energy, scientific argumentation, or systems and system models. The purpose of asking participants to engage in PLCs was to allow teachers to co-plan and teach lessons incorporating the NGSS and to collaboratively examine student work regarding specific DCIs, SEPs, and CCCs.

Data Sources

Participants in all three years of the project participated in school-based focus group interviews to elicit their understanding and implementation of the NGSS, especially regarding the interweaving nature of the three dimensions of the NGSS. Focus group interviews were conducted immediately following the Year Two five-day PD on waves and models and again immediately following the Year

Three five-day PD on states of matter. Ingrid and Tom (authors 1 and 3) conducted Year Two interviews, which included six focus groups; William and Tom (authors 2 and 3) conducted Year Three interviews, which consisted of three focus groups (see Appendix A for interview protocols). Interviews were not conducted after Year One because formative assessment information from throughout the first-year summer PD guided the leadership team to judge that teachers were still growing in their understanding of NGSS instruction. An interview may have unintentionally emphasized areas uncomfortable for teachers at this early stage of development and left a negative impression on teachers' perceptions of their progress.

Data Analysis

Interview data from Year Two was fully transcribed and analyzed using open coding (Creswell & Creswell, 2018; Merriam & Tisdell, 2016; Saldaña, 2013) to elicit emergent themes. Year Two analysis focused on themes related to understanding the three dimensions of NGSS. Ingrid and William (authors 1 and 2) open-coded the data individually and then discussed emergent themes together. Axial coding resulted in the themes that were consolidated into the following foci: understanding the complexity of the standards, utility of Bybee's (2013) foreground/background approach, pedagogical growth in understanding of how to teach the NGSS, and collaboration/vertical teaming. Ingrid and William then coded Year Two interview data for these four themes and discussed their coding.

After Year Three data were collected, audio files were fully transcribed, and Ingrid and William coded using the four themes that emerged from Year Two interviews. Ingrid and William quickly realized that new themes were evident and that the previous four could be refined. They revised the Year Two themes to be more specific and to include new components of Year Three interviews. See Table 5.

Table 5

Themes and Codes Applied to All Data (Year Two and Year Three)

Theme	Subthemes
Complexity of the Standards (C)	Complexity of interweaving the three dimensions (IW) • Foreground/Background (FB) • Intentional (I) • Explicit (E) Complexity of the content itself (COM)
Collaboration (Col)	Vertical progression/teaming (V) PLC work (PLC) Providing PD support to teachers and/or observing peers (SUP)
Reflecting on Teaching (R)*	Thinking about past instruction (PI) Having low PCK and/or gaining PCK new content/misconceptions (PCK)
Reflecting on components of PD (PD)	Product - learning content (PROD) Process - thinking about content in new ways (PROC) Pedagogy - classroom implications (PED)

Note. *Subsumed within other themes in the "Results" section for clarity

Due to the complex nature of the Year Three interviews and the large number of codes, Ingrid and William engaged in collaborative coding (Smagorinsky, 2008), discussing each talk segment and determining together the best code for the talk segment. All interview transcripts were discussed in-depth, and in cases where no codes fit the segment, Ingrid and William labeled it "no code". Initially, two Year Three transcripts were coded collaboratively in their entirety. Once Ingrid and William felt more comfortable in their mutual understanding of the codes, the remaining transcripts (six from Year Two and one from Year Three) were coded individually and then discussed/coded collaboratively. Patton (2015) notes the importance of trustworthiness, credibility, and dependability of data analysis. Indeed, we spent much time with participants within the PD activities and during interviews. To support dependability, we followed a systematic process of allowing themes and codes to emerge from the data. Table 5 provides an overview of the themes and codes that emerged from the data.

Results

The following results are based on the coding scheme summarized in Table 5, and are organized by the emergent themes of complexity of the standards, collaboration, and reflecting on components of the PD. For clarity, data that were coded as "*reflecting on teaching*" was subsumed under the other three themes.

Complexity of the Standards

Some teachers initially felt overwhelmed by the complexity of the NGSS, especially regarding the three dimensions—how to interweave them and how they built up to the performance expectations. After Year Two, however, teachers were beginning to understand the complexity and multidimensionality of the standards. An elementary teacher noted,

> [N]ow this week I see the benefit of really trying to make sure that you are doing the 5Es…just really being intentional about how you present the material and really being intentional about making sure you apply the DCIs, the crosscutting [concepts], and the practices. I am starting to make those connections, where now I see the big picture, where at first, I was kind of confused (*C-IW-FB-I and C-IW, Year Two*).

Teachers stated that while previously only emphasizing the content, they now understood the importance of the other two dimensions and interweaving them to form a cohesive "rope." One elementary teacher noted, "But what really drove home to me is now taking it all and making it one piece, versus all these different pieces of the puzzle" (*PD-PED, Year Two*).

Furthermore, an elementary teacher noted how she previously focused only on content but now understands the importance of all three dimensions of the standards.

> One thing that has influenced me is to not just focus on that orange box [DCI], because I think that's where we all tend to go, so I think this has really helped me focus on that green [CCC] and blue [SEP] box, and recognize that they are all three equally valuable, and to drive that content home in order to meet the performance expectations, so that was huge for me (*C-IW, Year Two*).

The PD experiences, therefore, clarified how the NGSS differed from previous state standards and how they now contained various "threads" that must interweave to build into the ultimate learning goals and complexity of the performance expectations. For many teachers, there seemed to be two phases of understanding during the PD: the NGSS had to be "unpacked" and evaluated as individual parts, and those parts then had to be weaved back together into an instructional whole. These phases seemed to cement a fuller understanding of the NGSS for teachers.

Explicitness and Intentionality

Regarding the multidimensionality of the standards, teachers stated that they had a clearer understanding of being explicit with their students about the three dimensions during instruction and being intentional about including them in their planning. Thus, *explicitness* refers to being direct and naming the actual DCIs, SEPs, and/or CCCs in the lesson. *Intentionality* refers to paying attention to incorporating all three dimensions while planning science lessons.

In the PD program, Bybee's (2013) concept of foreground/background was used as a framework to understand explicitness and intentionality. The foreground/background stipulates that in any given lesson or unit, select dimensions of the NGSS can be explicitly emphasized while others are attended to more implicitly. Using this approach to think of the complexity of the standards, the teachers began to conceptualize how and when to make various dimensions of the NGSS explicit. The teachers noted the foreground/background framework for the three dimensions and how beneficial it was to interweave them into one lesson or unit. As mentioned previously, teachers stated that they had formerly emphasized the content, as this was the focus of the previous state standards. They noted the importance of the other dimensions of scientific knowledge and how understanding the NGSS helped them conceptualize how to address their full scope.

> The foreground/background that we were all talking about…in previous years you're always so focused on the content, the content, the content, and by doing this it's allowed you to realize that you can focus on something else, and they still get the content. But our focus would be a crosscutting concept or developing a model or something along those lines instead of just that DCI. As a teacher you sometimes get to that overwhelming point of 'we have to teach this, and this and this and this and how do I fit it all into one school year?' So that was really beneficial (*C-IW-FB, Year Two*).

This quote suggests how the teachers believed the foreground/background approach would allow them to emphasize other dimensions of the NGSS beyond the DCIs. This view differed from prior instruction that focused solely on content. An elementary science coach noted that while the district has long been promoting and supporting inquiry-based science, the adoption of NGSS required teachers to be more clear about how students are engaging in the science practices: "We've been doing FOSS modules and investigative science and inquiry for a long time in the district so the practices are easier for them to see, but being explicit about them, we're getting there now" (*C-IW-FB-E, Year Three*). Likewise, a middle school district science coach emphasized the importance of a "name it and claim it" approach—in other words, being explicit with the students about the DCIs, SEPs, and/or CCCs connected to the lesson. One elementary teacher reflected on the importance of being explicit about the dimension she is foregrounding.

> And just being explicit with, um, talking to our students about modeling or cause and effect, or ya know, those other sides of the standards that aren't just the content piece but being real explicit in what we are saying and making sure that they are getting the point of an investigation or um, the activity in class (*C-IW-FB-E, Year Three*).

Regarding intentionality, teachers noted that to emphasize various dimensions of the NGSS, they needed to be purposeful in their planning. A middle school teacher reflected on her past teaching and stated the importance of being deliberate in her planning to include all three dimensions of the standards. She had previously discussed the SEPs and CCCs sporadically but will now be more intntional about focusing on these two dimensions.

> It's really deepened to a level of looking at like the DCI, and then looking at the engineering practices and then looking at your crosscutting concepts, but us really going through and doing those, and actually right now I feel better in the sense of like, what you said about being more intentional.

An elementary science coach spoke about how the PD would impact her as she developed the instructional units to be taught by teachers. She realized that she had to be more intentional and explicit as she wrote the units to guide teachers toward being explicit with their students about the dimensions of the standards.

> So, being very intentional in your planning… we've tried to be intentional with that foreground/background thing that [PD team member] brought up about definitely the DCIs are in the foreground kinda constantly when we're planning those units, but we've really tried to pull some of the practices into the foreground, and we would put teacher notes in those instructional units that say, 'the purpose of this is to intentionally focus the students on scientific writing…' but again it's letting the teacher know, but we didn't do a good job letting the teacher know that they need to intentionally teach that this is what they're doing (*C-IW-FB-I, Year Two*).

In this quote, the elementary school science coach reflected on how she planned to embed specific language to indicate to the teachers that they must be explicit in their discussions of the three dimensions. Thus, she planned to be intentional as she wrote units for the district. She noted that she had to be more purposeful about guiding teachers to verbalize reference to the three dimensions so that students knew when they were engaging in the SEPs and CCCs. This highlighted for the PD provider team the importance of explicitness and intentionality across multiple levels of teaching—in planning and delivery of PD experiences, by district science curriculum writers in communicating to classroom teachers who would use that curriculum, and by classroom teachers to explicitly teach SEPs and CCCs to their K-12 students. An unbroken chain of explicitness and intentionality seemed necessary to ensure that the ultimate multidimensional learning goals for students would be within reach.

Collaboration

Throughout the first two years of the PD program, teachers met in K-12 teams to discuss student work, examine content knowledge, and work with the standards. When discussing the benefits of collaboration, teachers noted the value of working in K-12 vertical teams and giving and receiving support from their colleagues. In the summer PD of Year Two, teachers physically mapped out the learning progressions of standards, examining and posting concepts linearly around the room to indicate how concepts deepened across each grade band. This helped many teachers understand the conceptual progression of the standards, gaining insight into what students needed to know both as a foundation for the specific concepts they teach and what students would be learning after their grade level.

Vertical Teaming

Teachers noted the importance of vertical teams (working in groups of K-12 teachers) and understanding the full spectrum of students' K-12 learning experiences. One elementary school teacher noted that she did not realize that the elementary science concepts were at such a simplified level and how complex the content became as students progressed to middle school.

> Well, I always think of, like when they were saying yesterday, like [indistinguishable] teaching waves in 4th grade and how much they have to know for the chemistry aspect in middle school, I mean it was pretty amazing when we were kind of like 'what did this experience, what concept were we trying to get?' I mean, I just thought it was funny, we're so broad and basic because that's really elementary, and then how narrow and focused [secondary teachers] were with what they thought the concept was, I mean, ya know it's the same thing, it's the same words but it's how you say them. And, just, it's just more complex as they get older and that was an eye opener for me (*PD-PROC, Year Three*).

This elementary teacher realized that the foundational knowledge she taught in fourth grade was critical to the concepts that were taught in later grades. Similarly, a high school teacher reflected on the importance of collaborating with K-12 teachers, thus gaining a deeper understanding of what students should learn before taking his class.

> And then another thing I thought that we learned that was very significant to me was what students should or would be doing in the vertical progression, because it helps me know what they should have seen, what they should understand, where they're coming from, and where we're getting them to. And it makes a really big difference to me knowing that they should have been introduced to waves in 7th grade, or they will be getting introduced to waves, that way I don't have to go over this is what a wave is and the very basics (*COL-V, Year Two*).

The teachers discussed that the K-12 nature of the PD gave them a better understanding of what their students needed to know, and it helped them build their content knowledge or understand the content in new ways. An elementary teacher noted the importance of verticalteaming to develop her content knowledge.

> But the big takeaway for me is the content knowledge and sitting K-12, because sitting with just elementary, there is a ceiling [with regard to content knowledge]. There is not as much of a ceiling when you have K-12 and when you have university specialists (*COL-V, Year Two*).

This data indicates that the opportunity to work in K-12 teams was a valuable part of learning about the standards, developing their content knowledge, and understanding the learning progressions of the concepts within NGSS.

Providing Support

Another critical aspect of the PD included teachers providing support for one another. The PD team explicitly planned some of this support, for example, the expectation of conducting three PLC cycles throughout Year One and participation in PD days during the year to examine students' work. The teachers noted that the PLC work supported their understanding of teaching the NGSS and the importance of embedding SEPs and CCCs. Recall that teachers were asked to focus on one of each of the three cycles on Energy, scientific argumentation, and systems and system models. The high school and elementary teachers stated that working in these PLC cycles allowed them to compare content across subject areas (i.e., high school physics to high school chemistry) and to impact students' learning. One elementary teacher spoke about the power of collaborating with the school science coach in the planning and teaching of a lesson focused on systems and system models.

> I think [teaching about systems] made the most impact on my kids because throughout the year they kept saying, 'I remember when we went out with [school science coach] and we did this animal dispersal. You know, I think that made a big impact on them (*COL-SUP, Year Two*).

In Year Three, the district science coaches reflected on their role in supporting the teachers in the project and the other teachers in the district. In addition, district science coaches reflected on their roles in developing instructional units for teachers from the current curriculum. They stated that they had worked directly with teachers in the classroom to support understanding and, in the future, they will presumably support the implementation of the new standards.

> So, um, a lot of our work this year has been helping teachers [who are not in the program], kind of where we started three years ago…getting teachers to dig into the appendix, dig into the progressions, look at vertical, the vertical progressions (*COL-SUP, Year Three*).

The coaches knew that participation in the project was not extended to all teachers in the district; therefore, their role was to support teachers not involved in the project to understand the standards and intentionally plan for and explicitly teach the three interweaving dimensions.

Reflecting on Components of the Professional Development

The final theme evident in the interviews was reflection on the various components of the PD. Teachers reflected on their understanding of content, learning new concepts, and thinking about content in new ways. Teachers also reflected deeply on how the PD would affect their future teaching and pedagogical practices.

Content

An essential goal of the PD project was to build on teachers' content knowledge, especially concepts related to Energy, other concepts from the NGSS that were absent in the previous state standards, and understandings of the three dimensions. Many of the elementary teachers reflected on the content that they learned in the program, even though some stated that they struggled with understanding at the level of the middle and high school teachers. One elementary teacher reflected on the importance of content knowledge when teaching and how having a deeper understanding could support her students' learning.

> But it was nice to be able to learn more myself to be able to go beyond that, in case the kids start probing or asking more questions, and I would be able to push them along and enlighten them a little further (*PD-PROD, Year Two*).

Furthermore, the teachers noted that the PD helped them learn new content and understand it in new ways. This was most evident regarding the content of waves (as this content was not explicit in the previous state standards) and how to incorporate the CCCs. One elementary school science coach said,

> What helped me the most was the content knowledge for the week of Energy [Year Two] and the content knowledge for the week of waves [Year Three], and setting the parameters of what really defines a system, and how I am going to get that to an understanding for an elementary

> teacher, and a model, the same thing, because we tend to think of models and making a model of a cell, or a volcano, and that's the only kind of model we can have (*PD-PROC, Year Two*).

In Year Three, a district science coach stated that teachers must discuss models and the limitations of models—an idea that was also discussed during the PD on waves in Year Two. This teacher reflected on how she used to teach specific content using models; however through the PD, she gained new perspectives on teaching models and systems. She began to see waves as a model, perhaps about an activity during which we modeled components of waves using our bodies and body movement.

> So, thinking about, ya know, you can't just build your model. You've got to discuss limitations, you've got to revise it, you've got to use it, ya know, those kinds of things. So we've designed different activities that we've used in PD in terms of how the teachers work on that piece of it (*PD-PROC, Year Three*).

The teachers stated that while much of the content they needed to teach from the NGSS was not new, they had yet to think of it through the lens of the CCCs. Recall that the PD focused on the CCCs of Energy and Systems and System Models. The teachers stated that while they had previously taught about Energy or Systems, they had yet to do so in a way that the concepts were interwoven with the DCIs. One high school teacher said,

> So, I think in the future…I'll be able to look at models as a much more important starting point for instruction. I'll be able to look at the engineering practices and the argumentation as more crucial and happening all the time. After last summer, I felt like my understanding was stuck with Energy and everything we did was about Energy. And when we did systems, I tried to put systems in other places as well, but it really felt much better in just Energy. Whereas I think models, I can really put anywhere in my instruction (*PD-PROC, Year Two*).

This quote indicates that the teacher was thinking about the content in new ways, as he could ground his lesson in a CCC rather than a DCI.

Pedagogy

A significant theme in the data included reflection on how teachers planned to teach or were teaching with the NGSS. Indeed, one of the interview questions in both Years Two and Three directly asked teachers how the project influenced their thinking, planning, and teaching of the NGSS. The teachers reflected on their ability to adapt what they already did to align with the NGSS and interweave the standards' three dimensions. During the Year Two interviews, one high school teacher noted,

> And I think that as a teacher what I can really do is take the lessons that I do already and with some fairly quick analysis, figure out how to be more explicit with my students that what they're doing is NGSS. It's not going to be new content necessarily, but a lot of it's overlapping from before, it's just new emphases (*PD-PED, Year Two*).

This reflection on how he could infuse his prior knowledge of content and the curriculum with the new concepts of the NGSS indicated that his understanding of the NGSS included the three dimensions. Moreover, he suggested that the NGSS were not entirely new—they included new (and perhaps additional) areas of emphasis. Another high school teacher explained how he viewed these new areas of emphasis.

> With systems, I never really looked at that as something to include in my instruction... systems simplify things for the students and models make them visible to the students. In chemistry, there's a lot of complicated things happening and there's a lot of things you can't see. I think really systems and modeling is going to be very impactful on my instruction. But it was tough the first time around, 'Okay now's the time I have to do systems. What lesson is this? Okay let's make it systems.' As opposed to the other way around, let's take a systems approach and fill in the lesson, and thinking about them this way. It almost felt like when does it come? It comes now? Okay, we'll do it with endothermic/exothermic. It made sense then, but it still, like you said, felt forced a little (*PD-PED, Year Two*).

This high school teacher reflected on his past instruction and noted how he planned to approach his future instruction. Initially, he was trying to include systems in a lesson, whereas he had reversed his thinking into beginning with a systems approach and seeing how the lesson fit in with systems. This reversal of how he thought about the lesson indicated that his pedagogical thinking had shifted as he interweaved threads of the three dimensions and changed the emphasis of the lessons.

Discussion

The findings of this study indicate that focused and extended (in this case, three years) PD can foster teachers' understanding of the three intertwining dimensions of the NGSS. Prior research has noted the complexity of the standards (Haag & Megowan, 2015; Lederman & Lederman, 2015; Pruitt, 2014; Smith & Nadelson, 2017); however, we found that teachers could conceptualize the intertwining "rope" (Krajcik et al., 2014) and discuss how they would intentionally plan for and explicitly teach the three dimensions. In some cases, teachers described lessons in which they shifted the focus of their lesson to a CCC and allowed the content to move to the "background" (i.e., elementary and high school examples of systems and systems models being the foreground focus of the lesson). Bybee's (2013) framing of foreground/background concepts was valuable for helping teachers determine how to focus lessons on multiple dimensions throughout a unit. Indeed, this framework of emphasizing one dimension at a time and allowing the other dimensions to be evident, but not explicit (i.e., backgrounded), can allow teachers to stay focused during individual lessons. As the dimension that is foregrounded shifts throughout the unit, teachers can feel confident that they are emphasizing all aspects of the NGSS without focusing on them in each lesson. The foreground/background framing of the three dimensions across a unit can be one way to reduce the overwhelming complexity of the standards, explicitly highlighting individual dimensions in each lesson, while still focusing on the intertwining rope across the unit.

The *Framework* (NRC, 2012) proposes that understanding the vertical progressions of concepts is essential to teaching science. Results from this study suggest that it was powerful for teachers to work in vertical K-12 teams, perhaps most importantly because they understood the foundations of concepts and how they become more complex throughout the grade levels. This finding aligns with the work of Gunning et al. (2020) and Trabona et al. (2019) and provides further evidence for the value of vertical teaming in NGSS PD. Indeed, in our study, elementary teachers noted that they were pushed when working with secondary teachers, and participants in all grade bands indicated that they developed a more profound understanding of the science dimensions. The opportunity to engage deeply in the learning progressions within the standards supports a greater understanding of NGSS by contextualizing grade-specific standards (Gunning et al., 2020). Penuel et al. (2014) emphasized the importance of content within the NGSS, and teachers stated that not only did they learn new content, but they viewed content in new ways. This is a vital aspect of reformed-based science teaching, as teachers begin to emphasize SEPs and CCCs in addition to DCIs to honor the intentional learning progressions across the three dimensions of NGSS (Willard, 2020). Indeed, science educators have called for a shift in how science is taught (Lee et al., 2014; NRC, 2012; Pruitt, 2014). While results from this study suggest that participants are starting to shift their thinking and instruction, they noted the need to tweak the practices and curriculum they are already using. This building on their prior practices is a crucial component of effective PD (Darling-Hammond & McLaughlin, 1995; Garet et al., 2001; NAS, 1996).

As previous studies have suggested, collegiality is vital to PD (Jeanpierre et al., 2005; Lieberman, 1995; Loucks-Horsley et al., 1998). We found that collaboration and support were critical to the success of PD on NGSS, and as did Gunning et al. (2020), specifically the opportunity for teachers to engage in discussion across K-12 grade bands. Exploring how ideas build across grade levels is a logical aspect of a deep conceptual understanding of the three dimensions.

Research has demonstrated that long-term PD is important (Garet et al., 2001; Luft, 2001; NAS, 1996; NRC, 1996; Supovitz & Turner, 2000), particularly for science teaching (Longhurst et al., 2016; Shymansky et al., 2012). We thus implemented a multi-year PD program to engage teachers authentically. This allowed them to deconstruct and understand the individual components of the NGSS and then to see the importance of putting them back together as a seamless whole. During the third year, evidence from the participants in our study suggested that this is when/where their daily classroom practice evolved to more fully embrace the core tenets of the NGSS. Collectively, this underscores the complexity of the standards and the teaching shift we are asking of our teachers. It also offers insight into the time it may take for individuals to shift their daily teaching practices substantially. In this district, science coaches will follow up with teachers and train teachers outside the program about the NGSS. While the level of intensity of the training will likely be lower, we have confidence that the science coaches will reach all teachers in the district. We hope the science coaches can model and discuss instruction that highlights an interweaving of the three dimensions (Krajcik et al., 2014) through a foreground/background approach (Bybee, 2013). Furthermore, we posit that further collaboration through PLCs within and across schools could foster a deep understanding and powerful implementation of NGSS.

We thus conclude that the unique combination of three elements of our multi-year NGSS PD program—vertical teaming, a focus on conceptual understanding, and collaborative discussion to plan for NGSS implementation, particularly in adapting curriculum—was valuable and critical. Results from this study suggest that working in collaborative teams to explore specific DCIs, SEPs, and CCCs through active science inquiry experiences allowed teachers to understand the interweaving three dimensions of the NGSS. While active learning (Darling-Hammond & McLaughlin, 1995) and collegiality (Jeanpierre et al., 2005) are vital components of PD, our program focused on fostering vertical conversations and collaboration (which included PLC work). Indeed, participants stated that these were critical aspects of understanding the dimensions of the NGSS. Similar to Gunning et al. (2020), the teachers in our study demonstrated a deeper understanding of the three dimensions of NGSS through vertical teaming and PLCs, yet our study involved a three-year PD (one year longer than that of Gunning et al.) that adapted to the needs of the teacher participants. As mentioned previously, a key element of our PD was using Bybee's (2013) conceptualization of foregrounding/backgrounding dimensions of the NGSS throughout the unit. This feature adds to the literature base by suggesting a framing of the dimensions to simplify instruction over time. The foreground/background approach may offer teachers a way to teach the three dimensions in a less complex manner, streamlining the focus of each lesson within a unit. We believe this is a powerful framing for PD and instructional planning, allowing teachers to explicitly teach each dimension, perhaps earlier in the unit, while intentionally intertwining the dimensions throughout instruction. This intertwining should also be made explicit within the unit. Finally, our study adds to the literature on PD for the NGSS. It examined the three elements and offered a way to implement the three intertwining strands across a unit by foregrounding/backgrounding individual strands in each lesson.

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Appendix A

Year Two and Year Three Focus Group Interview Protocol

Questions for Teachers Who Participated All Three Years

1. (Present participants with a list of the project components). Which component or components of the project were the most impactful on your teaching and why?
    a. Probe: Example from your teaching?
    b. **Probe based on themes from Year Two Interviews:** In what ways has Bybee's foreground/background approach affected your teaching and planning? In what ways has the format of working K-12 affected your planning and teaching? *(Year Three only)*
2. How has the project influenced your thinking, planning, and or teaching of the three dimensions of NGSS?
    a. **Probe based on themes from Year Two Interviews:** In what ways has the project influenced your: 1) understanding of the complexity of the NGSS? 2) Pedagogical growth? *(Year Three only)*
3. What supports do you still need? *(Year Two only)*
4. Of the three PLC cycles you did as a school, which do you think was most successful and why? Which was the most challenging and why? *(PLC groups only)*

Year Three Questions for New Participants

1. (Present participants with a list of the year 2 project components). Which component or components of the project were the most impactful on your teaching and why?
    a. Probe: Example from your teaching?
2. How has the project influenced your thinking, planning, and or teaching of the three dimensions of NGSS?

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What are They Good For? The Importance and Value of NGSS Science Practices

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ABSTRACT

This study aimed to identify the Next Generation Science Standards (NGSS) science practices secondary science teachers considered as most important, to determine what type of value teachers ascribed to those practices, and to examine any correlations between teachers' perceived importance of the practices and their self-reported implementation. An electronic survey was used to collect multiple forms of data from 128 secondary science teachers. Quantitative data was analyzed using descriptive statistics, average ranking scores, and Spearman's rank correlation coefficient. Qualitative data was analyzed through qualitative content analysis using Wigfield and Eccles' (2000) Expectancy-Value Theory (EVT) as an analytic framework. Our findings indicate that: (1) teachers ranked asking questions as the most important science practice, and mathematics and computational thinking as least important; (2) teachers most frequently attached attainment value to the usefulness of the practices; and (3) the correlations between teachers' rankings of the practices and their self-reported implementation were mixed. The rank-implementation mismatches can be interpreted as an outcome of teachers' misconceptions about some of the science practices. This study highlights the need for teacher education initiatives that promote teachers' implementation of and long-term utility value of proficiency with all eight of the science practices.

Keywords: NGSS science practices, Expectancy Value Theory, teachers' values, science practice implementation, teacher education

Introduction

Science education in the United States (US) has been criticized for focusing on unidirectional transmission of science content from teacher to student and rote memorization of scientific facts (Osborne, 2014; Richmond et al., 2016). Alternatively, there has been a growing consensus in science education literature that science consists of a series of practices, and thus, science practices should be placed at the center of science teaching and learning (Aleixandre & Crujeiras, 2017; Duschl, 2008; Osborne, 2014). The emphasis on science-as-practice was translated into policy documents such as the Framework for K-12 science education (National Research Council [NRC], 2012) and the Next Generation Science Standards ([NGSS], NGSS Lead States, 2013a) in the US. The term "practice" is specifically used to highlight that for students to engage in authentic science investigations, they need not only skills but also knowledge specific to each science practice (NRC, 2012). Prioritizing science practices represents the significance of involving students in core science practices as a means to achieve cognitive, epistemic, and social learning goals in science (Duschl, 2008; NGSS Lead States, 2013a).

To address these concerns, the introduction of the NGSS aimed to transform approaches to science education by emphasizing science as an ongoing process rather than presenting it as static facts. The NGSS put forth eight key science practices that students should learn to grasp Disciplinary Core Ideas (DCIs), Crosscutting Concepts (CCCs), and the epistemology of science (NGSS Lead States, 2013a). These practices include: (1) asking questions, (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, (7) engaging in argument from evidence, and (8) obtaining, evaluating, and communicating information (NGSS Lead States, 2013a). Acknowledging that helping students develop knowledge of, and proficiency with, these practices will take time and purposeful instruction. In fact, the NGSS explicitly states that "students in grades K-12 should engage in all eight practices over each grade band" (NGSS Lead States, 2013a, p. 2), and suggests these practices should be interwoven into instruction in a coherent learning progression.

While research shows that engaging students in science practices enhances their understanding of science content, processes, and epistemic knowledge, doing so imposes profound demands on teachers (Crawford & Capps, 2016; Nollmeyer & Bangert, 2017) and teachers often struggle to implement the practices (e.g., McNeill et al., 2017). There must be a shift in science teachers' epistemological, procedural, and conceptual understanding of science (Crawford & Capps, 2016; Kite et al., 2021). Hence, there is an imperative need for research that provides insight into how to support science teachers' implementation of science practices. The present study responds to this call by focusing on the value, a critical component of teachers' beliefs, that science teachers attribute to the science practices. This is because science teachers' implementation of the science practices requires a considerable shift in their beliefs, professional knowledge, and skills (Park et al., 2022).

Researchers have highlighted the role of science teachers' values in mediating their implementation of reformed science teaching practices (e.g., Herrington et al., 2016). Values have been conceptualized as highly personal and relatively durable drivers of an individuals' overarching worldview and behaviors (Schwartz, 1994; Wallace & Priestley, 2017). Herrington et al. (2016) noted that values are "a central driver for action" (p. 186) and demonstrated through their research that teachers with stronger values towards implementation of reformed teaching practices were more motivated to implement reformed teaching in their science classrooms. Likewise, Wigfield and Eccles (2000) posited that individuals' motivations to engage in a particular task depends on the value that they place on the task, as well as their expectancy for success. Consequently, we infer that there may be a relationship between the value that teachers place on each of the science practices and the likelihood of them implementing those practices in their classrooms. The logical consequence of this inference is that teachers may not expose their students to practices that they believe to be less valuable for learning.

Despite increased attention to the importance of engaging students with the NGSS science practices and the critical role of teachers' beliefs in their instructional practice, little effort has been directed towards examining secondary science teachers' perceived task value - a critical component of teacher beliefs - and the importance of each of the eight science practices. Although there is a notable body of literature on the relationship between teacher beliefs and practices in general (e.g., Martin et al., 2019; van Aalderen-Smeets & van der Molen, 2015; Wallace, 2014), research paying specific attention to task values is scarce (e.g., Herman et al., 2017; Herrington et al., 2016) despite its important role in teacher belief systems (Eccles & Wigfield, 2020). This study aimed to fill this gap.

In this study, we employed Expectancy-Value Theory (EVT) (Wigfield & Eccles, 2000) as a theoretical framework to qualitatively examine the science practices that secondary science teachers perceive as most important for students' science learning, with no relation to individual teachers' overall values for the practices, the value they ascribe to those practices, and the relationship between the practices they value and the practices they implement. This study was guided by the following questions:

(1) Which of the eight NGSS science practices do secondary science teachers consider most important and what value do they ascribe to those practices?
(2) What is the relationship between secondary science teachers' ascribed importance of each of the science practices and their self-reported implementation of each of the practices?

Findings from this study contribute to a better understanding of the relationships between teachers' values and their instruction -- especially with respect to the science practices that have received significant attention in the broader science education community beyond the US (Stroupe, 2015). In addition, this study will provide insights to inform strategies to promote teachers' implementation of the science-as-practice approach to teaching science from the perspective of teacher task value as an important motivational factor influencing instructional decisions.

Theoretical Frameworks

Science Practices as Both Process and Product of Students' Science Learning

Promoting students' scientific literacy has been an ongoing goal of science education reform and has informed national science standards in many countries including the US (e.g., NRC, 2012; Organization for Economic Co-operation and Development [OECD], 2019; Roberts & Bybee, 2014). Scientific literacy is defined as the ability to scientifically explain phenomena, engage in scientific inquiry, and interpret data and evidence through the integration of content, procedural, and epistemic knowledge (OECD, 2019). To facilitate this goal, the NGSS outline eight science practices to support students and teachers in navigating the larger cognitive, epistemic, and social learning goals of authentic scientific inquiry (Duschl, 2008). Through engaging in science practices, students can develop an understanding of how scientific knowledge is constructed and applied (Berland et al., 2016), internalizing "what we know, how we know, and the epistemic and procedural constructs that guide the practice of science" (Osborne, 2014, p. 183).

As conceptualized in the NGSS, these science practices represent both instructional strategies and learning outcomes. Rather than existing as discrete skills of scientific inquiry that can be mastered by students, teachers are to engage students in these eight practices on a regular basis as a means of building students' proficiency with each and to help students internalize the process and practice of contemporary science. The NGSS envisioned science classrooms where students build knowledge, skill, and epistemic understanding by "practicing" science (Bybee, 2011). Building classrooms rooted in rich scientific practice, however, depends on teachers understanding each of the practices and valuing the practices as both a process and product of student learning.

Teacher Beliefs, Values, and Practice

Teachers' beliefs and values about the nature of teaching and learning act as filters that guide their instructional decisions. A number of studies have suggested a positive association between teachers' beliefs and their decisions about both curriculum and pedagogy (Biesta et al., 2015; Suh &

Park, 2017; van Aalderen-Smeets & van der Molen, 2015; Wallace, 2014), and demonstrated that teachers' beliefs strongly influence their science teaching and the implementation of alternative forms of practice (Lotter et al., 2016; Lumpe et al., 2012; Martin et al., 2019). Particularly, teachers resist implementing innovative teaching approaches or curriculum materials that contradict their beliefs about either the purpose of teaching science or how science should be taught (Bryan, 2012; Wallace, 2014). Hence, for any reform movement that requires changes in teachers' practices to be successful should carefully consider teachers' beliefs.

Eccles (2009) provides some explanation of the relationship between teachers' beliefs, their values, and their instructional practice. Specifically, Eccles (2009) has pointed out that the likelihood of an individual engaging in an activity is driven by a combination of their beliefs about who they are, what they are good at, and the subjective value they place on an activity. If a teacher believes that an instructional approach is valuable for their students, and if they feel confident that they can adequately implement the strategy, then they are likely to pursue enactment. Herrington et al. (2016) highlighted the importance of science teachers' values in their work, demonstrating that teachers whose science teaching values shifted towards prioritizing long term student growth (utility value described below) during professional development were more likely to implement inquiry-based teaching with their students and to encourage their colleagues to do so as well. Further, Herman et al. (2017) showed that teachers with high utility value for teaching the nature of science (NOS) (i.e., they thought teaching NOS would prepare students to be scientifically literate, lifelong learners) demonstrated stronger implementation of NOS in their classrooms. Therefore, to support teachers to engage students in the science practices, it is necessary for science teachers to value the practices as critical to students' long-term success and believe them to be aligned with their own goals of science teaching. Understanding teachers' current individual values regarding the science practices is a critical first step towards this goal.

Expectancy-Value Theory (EVT)

EVT of achievement (Wigfield & Eccles, 2000) served as both a theoretical and analytic framework for our investigation of the value that secondary science teachers place on the science practices outlined in the NGSS. According to EVT, an individual's choice to engage in achievement-related activities is governed by both their expectancy for success and the value that they place on the activity or outcome (Wigfield & Eccles, 2000). EVT has been used in previous research as a model to understand science teachers' implementation of innovative pedagogies, but has yet to be applied to the context of the NGSS science practices (e.g., Lee & Blanchard, 2019). EVT identifies four key factors that shape an individual's decision to engage in an activity: intrinsic value or interest, attainment value or importance, utility value or usefulness, and cost (Eccles et al., 1983; Wigfield & Eccles, 2000). Eccles et al. (1983) defined intrinsic value as the enjoyment an individual experiences when engaging in a task. Attainment value is the importance of doing well on the given task, while utility value refers to how the task will affect an individual's future plans. Cost value has received minimal attention in research but is broadly concerned with how engaging in the task will affect participation in other activities, the effort required to complete the task, and the emotional costs (Wigfield & Eccles, 2000). In this study EVT served dual purposes. First, it was used to guide the development of our coding frame for qualitative content analysis. Specifically, EVT informed our four categories of values: interest - enhancing student motivation; attainment - achievement of immediate instructional goals or helping students achieve proficiency in scientific practices; utility - building students' skills for future application outside the classroom; cost - barriers to implementation of scientific practices in the classroom. Second, we interpreted the results of our analysis through EVT as a theoretical framework to draw conclusions regarding secondary science teachers' values of science practices in relation to their self-reported implementation of those practices.

Methods

Study Design

This study used an open-ended online survey administered to secondary science teachers in a Southeastern State in the U.S. Given the exploratory nature of this study and our goal of providing evidence of patterns among a large teacher population, we decided to use an open-ended survey instead of individual interviews (Kendall, 2008). Further, an open-ended survey allowed for data collection from a large and geographically dispersed population and gives anonymity to respondents that may encourage them to provide more honest responses (Bloch et al., 2011; Erickson & Kaplan, 2000). The design of and data collection for this work was approved by the [University] Institutional Review Board for the Use of Human Subjects in Research (Protocol #9432).

Participants

A Qualtrics survey link was distributed via email to 895 secondary science teachers. Participants consented to participate in the study by opening the survey and were offered a gift card upon completion of the survey and 128 teachers fully completed the survey. As shown in Table 1, our sample is fairly representative of the demographic characteristics of teachers in the state for the time period in which the data was collected (Department of Public Instruction, 2020).

Table 1

Demographic Characteristics of Teachers in the State and Study Participants (N = 128)

Characteristic	Sample	State
Gender		
Female	78%	80%
Male	22%	20%
Ethnicity		
European American/White	85%	81%
African American	10%	14%
Hispanic/Latino	2%	3%
Other	2%	1%
Native American	1%	1%
Educational Attainment		
Master's Degree	45%	
Bachelor's Degree	37%	
Some graduate level credit	18%	
School Level		
High School	63%	
Middle School	33%	

Each teacher was assigned an ID number (e.g., T1, T2, … T128) that will be used as an identifier throughout the manuscript. For context, the data for this study was collected prior to the COVID-19 pandemic in a State that has not adopted the NGSS.

Although the targeted state has not adopted the NGSS, our findings can still inform the literature about the gaps in teachers' values related to the science practices. First, the state in focus was one of the leading states for developing the NGSS but chose not to adopt them. Instead, it opted for newly introduced science standards that closely aligned with the NGSS (NGSS Lead States, n.d.). Therefore, it is reasonable to expect that science teachers in the state had experience with the science practices whether it was explicitly mandated or not. Second, the targeted state recently adopted the performance expectations of the NGSS for the state science learning standards, with science practices embedded in the standards (North Carolina Department of Public Instruction, 2023). Accordingly, these findings are useful to understand how science teachers in this state value the practices prior to implementation, to support professional development that considers their existing beliefs, knowledge, and skills about the science practices. The results of our work will also be most informative in locations that are also transitioning their science standards to align with the NGSS science practices.

Data Sources

Data analyzed for this study is drawn from the final section of a larger survey that consisted of three sections: (a) teachers' epistemic orientations to science teaching, (b) their epistemic understanding of the science practices, and (c) their self-reported implementation of the practices (Park et al., 2022). The section relevant to this study included the 18 questions presented in Appendices A and B. The first 16 questions were five-point Likert-scale questions (Never, Sometimes, About half the time, Frequently, or Always) asking how often teachers implement aspects of each of the eight science practices (two questions for each practice). The next two questions focused on teachers' perceived importance of the science practices: one drag-and-drop question asked teachers to rank the eight science practices from most important (1) to least important (8), and one open-ended question asked them to describe why they thought their top three practices were most important for students' science learning. Analysis of the construct validity of the 16 Likert scale items about science practice implementation revealed that one item (Imp05) about the practice of conducting scientific investigations was misfitting (Park et al., 2022). Consequently, we removed that item from our analysis. Appendix B shows that the Cronbach's Alpha value for the 15 items used in our analysis was $\alpha = 0.928$.

Data Analysis

Analysis of Likert Scale and Ranked Items

Teacher responses to the 15 Likert-style implementation questions were converted to 5-point scale scores from Never = 1 to Always = 5. Implementation scores from the two Likert-style questions associated with each practice were averaged and descriptive statistics were calculated to identify trends in teachers' self-reported implementation of each practice. Next, teacher responses to the drag-and-drop ranking question were analyzed using descriptive statistics, average ranking scores were calculated for each practice, and the frequency with which each practice was selected as one of the teachers' top three was determined. Finally, Spearman rank-order correlations were calculated to identify any significant relationships between responding teachers' rankings of the science practices and their reported implementation of individual practices; the assumption being that a higher ranking for a practice should correlate with more frequent implementation.

Analysis of Open-ended Responses

Teacher responses to the open-ended question were analyzed using qualitative content analysis (Schreier, 2014) with Atlas.ti as an aid. First, a coding frame was developed that consisted of both concept-driven and data-driven categories (Mayring, 2015). The four main concept-driven categories were derived from the EVT as described above (i.e., interest, attainment value, utility value, cost). Next, data-driven subcategories under each main category were developed through open-coding and defined in a way to ensure mutual exclusiveness between sub-categories (Schreier, 2014). The coding frame was revised and finalized through a pilot phase of an iterative process involving two researchers. First, the two researchers independently coded the same 10% of the responses, compared and discussed the codes until they reached agreement, then revised and refined the initial coding frame. Next, the same two researchers independently coded another 20% of the responses using the revised coding frame and, again, compared and revised the codes to finalize the coding frame. Following the finalization of the coding frame, Atlas.ti was used to calculate Krippendorff's alpha of 0.989 (Krippendorff, 2011). Finally, analysis moved to the main phase in which each researcher coded 50% of the remaining data independently using the final coding frame (Schreier, 2014). See Table 3 and Appendix C for this information.

Results

Through our analysis we investigated which of the eight NGSS science practices teachers believed were most valuable, the type of value that they believed inclusion of the science practices would have in their instruction, and correlations between teachers' rankings of the practices and their self-reported implementation of the practices. The results of our analysis are presented below, organized by research questions.

RQ 1: Teachers' Prioritized Science Practices and Ascribed Value

Analysis of teachers' rankings of the eight practices revealed that teachers believed that the practice of asking questions was most important. Content analysis of their justifications for their rankings showed that teachers thought that questioning was most useful as a means of monitoring student learning. Regarding the EVT categories, teachers primarily focused on the attainment value of the practices. A full reporting of our findings follows.

Teachers Prioritized Asking Questions

Data analysis revealed that teachers in this study prioritized asking questions ($M = 1.93$, $SD = 1.70$) as the most important practice for student science learning, followed by analyzing and interpreting data, and constructing explanations. Table 2 presents participants' mean ranking score, the standard deviation, and number of times a practice was identified as a "top three" for each of the science practices (i.e., Frequency).

Table 2

Average Importance Ranking Scores of the Science Practices (N=128)

Science Practice	M	SD	95% CI	Frequency
Asking Questions	1.93	1.70	[1.635, 2.225]	106
Analyzing and Interpreting Data	3.51	1.49	[3.252, 3.768]	65
Constructing Explanations	4.28	1.62	[3.999, 4.561]	42
Developing and Using Models	4.73	2.10	[4.366, 5.094]	43
Planning and Carrying out Investigations	4.73	2.33	[4.326, 5.134]	51
Obtaining, Evaluating, and Communicating Information	4.95	2.04	[4.597, 5.303]	37
Engaging in Argument from Evidence	5.43	2.17	[5.054, 5.806]	30
Using Mathematics and Computational Thinking	6.44	1.79	[6.130, 6.750]	10

Mean scores closer to 1 indicate that a practice was frequently given first rank and mean scores closer to 8 denote a practice that was frequently ranked last.

It is worth noting that some of the practices were more frequently listed as one of the "top three" practices, but did not have a top three average. For example, planning and carrying out investigations was the third most frequent response (*n* = 51) but was fifth in terms of mean ranking (*M* = 4.73, *SD* = 2.33). We conducted a one-way ANOVA to compare the means and confidence intervals of the three mid-ranked practices (explanations, models, and investigations). The test revealed that there was not a significant difference between the mean rankings, *F*(2, 381) = 2.11, *p* = .122, and the confidence intervals mostly overlap. This could explain why some of the practices have a higher frequency but lower ranking.

Teachers selected asking questions as the most important practice for two primary reasons: (a) many viewed questioning as a fundamental component of science (*n* =19) and (b) a majority saw questioning as a means of monitoring students' engagement and learning (*n* =63). Most teachers viewed questioning as a fundamental component of science because asking questions is the start of inquiry (*n* = 12) and is the foundation of science (*n* = 6). As one teacher (T5) stated, "Asking questions is what science is all about." Though teachers often wrote about questioning as being an important component of science, they more frequently described the practice as an important tool for monitoring students' engagement and learning (*n* = 63). Specifically, several teachers (*n* = 31) stated that asking questions shows [engagement, curiosity, critical thinking, metacognition]. This view is well reflected in T9's response: "Students must be engaged or interested in topics to really digest the information and asking questions shows interest" (T9). Additionally, some teachers indicated that asking questions is the basis for understanding as shown in T8's response: "In order for students to understand they need to ask questions." Notably absent from teachers' responses were any mentions of scientific questions as a tool for critique.

Teachers' Predominantly Ascribed Attainment Value to the Practices

Our content analysis indicated that the teachers primarily attributed attainment value to their prioritized science practices. See Table 3 for this information.

Table 3

EVT (Wigfield & Eccles, 2000) Coding Frame with Quotation Frequencies (N = 285)

Categories (*n*)	Sub-category	Frequency	Percent
Attainment		198	69.47
	Enhancing Conceptual Understanding	73	25.61
	Engaging in practices of science	54	18.94
	Developing student thinking skills	39	13.68
	Building students' understanding of the nature of science	32	11.23
Interest		57	20.00
	Enhancing student interest	36	12.63
	Building student motivation	21	7.37
Utility		18	6.32
	Building transferable skills	18	6.32
Cost/Barriers		12	4.21
	Teachers' negative perceptions of students	8	2.81
	Standards and testing	4	1.40

That is, they viewed the science practices as a means of accomplishing instructional goals like enhancing student conceptual understanding, engaging students in the practices of science, developing student thinking skills, and building students' understanding of the nature of science. Capturing the ideas of enhancing conceptual understanding and engaging in the practices of science, T74 highlighted both their belief about what science education should be and the role of the science practices in enhancing science learning in their statement that, "students need to be able to investigate, ask questions, and develop/use models to foster their understanding of science. This is what science is and should be rather than learning facts from a textbook." Another common thread under the theme of enhancing conceptual understanding was the idea of deep learning (*n* = 24). In other words, the science practices are an avenue through which students will develop deeper understandings of disciplinary content. Characteristic of this idea was T57 who mentioned that "coming up with and conducting your own experiment is crucial to students' true understanding of the subject."

The second most prominent value that teachers ascribed to the science practices was Interest. Common ideas under interest indicate that teachers felt that the science practices were useful for engaging students, giving students ownership, and piquing student curiosity. Speaking collectively of their three top science practices, T124 noted that "They [the science practices] help to create a classroom of student engagement." Similarly, T54 stated that "Asking questions is critical to engaging students in the learning process." Regarding the idea of giving students ownership, T38 asserted that "If they [students] construct their own explanations rather than being spoon-fed everything from a teacher, they take ownership of their learning and achieve higher results."

Interestingly, only 18 teachers ascribed utility value to the science practices. All of these quotations indicated that the teachers view the science practice as useful for helping students Build transferable skills that will support students in their future endeavors. Referring to the practice of constructing arguments, T72 said that "Making informed arguments is what our students need to do even if they do not follow a STEM path. It will help them make their own decisions in life." Similarly, T114 stated that "If they [students] can engage in this type of discourse and investigation in class with me, then those skills are transferable to their lives outside of the classroom."

Though teachers were not asked to identify barriers to implementing the eight science practices in their classrooms, 12 teachers described challenges that they believed might prevent them from including the practices in their instruction. As shown in Table 3, the noted barriers included teachers' negative perceptions of their students and standards and testing. T100 noted that "I work with mostly standard-level students, so asking questions is my biggest challenge." Speaking to multiple practices, T60 explained the following

> I have seen students struggle the most within the scientific method in the analysis of data (what the heck is it telling you), how to then use the data to develop an explanation of the results, and the idea that math can and should be used to help interpret experimental results.

Finally, in a disheartening depiction of the influence of standardized testing on science education, T86 concludes that

> Teachers are judged and scored on a Multiple Choice test!!!!! The top three [science practices] give the best results for test taking skills, I would love to spend more time doing science versus preparing students for a test, the test is pressure on students, and results are used against teachers, some of our best scientists and minds would fail such tests.

Notably, all the science practices that were attached to barriers to implementation in the classroom received middle to low rankings on both value and reported implementation, and include: planning and carrying out investigations, developing and using models, analyzing and interpreting data, and using mathematics and computational thinking.

RQ 2: Relationships Between Teachers' Practice Rankings and their Reported Implementation

Teachers' average reported frequency of implementation for all eight of the science practices was 2.69 (*SD* = 0.95, 95% CI [2.52, 2.85]), which translates to less than half the time. As shown in Table 4, we found mismatches between the practices that were ranked as most important and the practices that were reported as most-frequently implemented.

Table 4

Correlations Between Teachers' Ranking for Each Science Practice and Reported Frequency of Implementation (N = 128).

Practice	Importance Ranking	Average Importance	Average Implementation	Correlation Coefficient	*p*
Developing and using models	4	4.73	2.543	-0.315	0.001***
Planning and carrying out investigations	5	4.73	2.328	-0.272	0.002**
Using mathematics and computational thinking	8	6.44	2.555	-0.206	0.020*
Engaging in argument from evidence	7	5.43	2.613	-0.162	0.067
Constructing explanations	3	4.28	3.160	0.154	0.083
Analyzing and interpreting data	2	3.51	2.816	-0.079	0.373
Obtaining, evaluating, and communicating information	6	4.95	2.828	-0.056	0.527
Asking questions	1	1.93	2.641	0.023	0.792

Note. Negative correlation coefficients are to be expected because higher ranking scores move closer to 1 while higher implementation scores move further from 1; meaning the values are moving in opposite directions.***$p < 0.001$, ** $p < 0.01$, *$p < 0.05$

For example, while asking questions was the highest ranked of all practices, it was the fifth most implemented practice (less than half the time). Likewise, constructing explanations was the only practice that teachers reported implementing about half the time but was ranked as third most important.

Conversely, there were significant correlations found between teachers' importance rankings and reported implementations for three of the science practices: modeling, $r_s(126) = -0.31$, $p = .001$; investigations, $r_s(126) = -0.27$, $p = .002$; and computational thinking, $r_s(126) = -0.20$, $p = .020$, as seen in Table 4. Overall, the correlations fell roughly into two categories. There was significant alignment between teachers' low levels of implementation and their low rankings for three practices (modeling, investigations, and computational thinking).

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Notable mismatches emerged between teachers' relatively high ranking and average implementation of analyzing and interpreting data; their relatively low ranking and average implementation of obtaining and evaluating information; and their high rank and average implementation of questioning. We urge a cautious interpretation of these results as teachers' frequency of implementation was self-reported and the average implementation scores for the majority of the practices (except investigations and explanations) fall within the same confidence interval.

Limitations

We urge a cautious interpretation of our findings for three reasons. First, our findings are based on responses from only 14% (*N* = 128) of our target sample. Consequently, the findings of this study may be most applicable to the teachers who provided data. We note, however, that our sample of teachers are demographically similar to teachers in the state where the data was collected. Second, the study uses self-reported implementation data without corroborating observational data. Although large scale self-reported survey data can match observational data (Gibbons et al., 2018), research has noted that teachers' self-reported data can elicit socially desirable and biased responses (e.g., Cross Francis et al., 2015; Desimone, 2009). These biased responses could explain the observed mismatches between teachers' reported implementation and perceived importance of the science practices. As such, the findings should be interpreted cautiously, and further research should consider combining short-term and longitudinal self-report and observational data (Desimone, 2009). Third, our data comes from a single state in the US that has not adopted the NGSS, and we did not collect data about teachers' prior exposure to the NGSS. Thus, teachers' prior exposure to the NGSS could have influenced their responses in a manner that we were not able to account for. These limitations provide opportunities for future research. Future studies that involve a larger sample of secondary science teachers in different settings and with different levels of NGSS professional development experience would expand our understanding of the value and importance that teachers place on the NGSS science practices. Research in this vein could investigate differences in value and importance between teachers from states that have, and have not, adopted the NGSS as well as teachers with different NGSS professional development opportunities.

Discussion and Implications

This study explored science teachers' perceived value and importance of the eight science practices, and the relationship between the practices they value and self-reported implementation of each of the practices. Our findings provide useful insights to inform efforts to better support secondary science teachers' implementations of the NGSS science practices.

Perceived Importance and Value

In response to our first research question, we found that teachers considered asking questions as the most important science practice because they believed that it supports student science learning through enhancing student engagement and giving students ownership of their learning. While provoking student interest and motivation is an important outcome of participation in the science practices, the NGSS model of three-dimensional (3D) learning stresses that students should engage in all eight practices as epistemically coherent practices that build students' understanding of crosscutting concepts, disciplinary core ideas, and the epistemology of science (NRC, 2012). Participants' value of scientific questioning primarily to monitor student progress indicates that they may not fully understand both the ways in which scientific questions are interwoven with other practices, and the role of questioning in scientific critique. This limited view could prevent teachers from supporting their students in understanding questioning as a part of the intertwined yet coherent process of scientific inquiry (Berland et al., 2016; Capps & Crawford, 2013; Kite et al., 2021). Thus, science teacher professional development initiatives should provide learning opportunities that engage the teachers in a range of activities that require developing scientific questions for further investigation and using questioning to critique models and investigative designs.

Despite an increased focus on supporting teachers to effectively implement computational thinking (CT) in their classrooms (Li et al., 2021; Yadav et al., 2017), the teachers did not see this practice as being applicable beyond the classroom and did not value this practice as a means of either motivating students or building their scientific competency. The low level of both priority and value that teachers placed on this practice may be an artifact of their uninformed understanding of CT (Kite & Park, 2023). Research has identified several factors hindering science teachers' understanding and implementation of CT: very few examples of CT-integrated science curriculum, minimal exposure to CT in their teacher preparation program, and prevalent beliefs that CT is simply using mathematics and computers (Sands et al., 2018; Yadav et al., 2017). In this respect, science teacher professional development initiatives will need to make the role of CT in contemporary science clear to their teachers and engage them in both programming-based and technology-free activities that demonstrate how CT can be infused into science curriculum (Kite & Park, 2023; Peel et al., 2020).

It is interesting that teachers value the scientific practices most as a means of meeting immediate instructional goals (i.e. attainment value) and less as a means of either enhancing student motivation (i.e. interest value), or providing students with skills for the future (i.e. utility value). Considering Herman et al.'s (2017) findings that high utility value of teaching the NOS corresponded with higher quality implementation of NOS teaching, the high attainment value that teachers in our study placed on the science practices could be problematic. This is because teachers may prioritize providing their students with superficial science practice experiences to solidify content understanding, rather than engaging them deeply in the science practices as a means of developing critical thinkers who can operate as scientifically literate citizens (OECD, 2019).

Keeping the above in mind, more attention must be devoted to both identifying and shifting the value that teachers place on the practices to promote their effective implementation of the practices. Research has shown that collaboration with other teachers and participation in content-related tasks and activities that model the NGSS science practices can improve teachers' self-reported knowledge, implementation, and epistemic values related to the science practices (Christian et al., 2021). Initiating a shift in teachers' values may be challenging, but not impossible. A growing number of studies have also indicated that experiences with systematic teacher education programs play a critical role in facilitating meaningful changes in teachers' beliefs, values, and practices (Herrington et al., 2016; Lotter et al., 2016: Luft, 2001; Lumpe et al., 2012). Thus, teacher preparation programs also have an important role in helping teachers understand the utility value of the NGSS science practices.

Teachers' reference of barriers (i.e., Costs) to implementing the science practices bears mentioning because the question prompt did not ask teachers to identify barriers to implementation. Nonetheless, participants cited low-level students and accountability regimes as significant barriers to implementing the practices in their classrooms. These results are concerning because research has shown that teachers' beliefs about both their students' abilities and contextual constraints can prevent teachers from attempting to engage their students in more rigorous, practice-based work (Abrami et al., 2004; Day, 2020; Savasci & Berlin, 2012). Any interventions to support the science-as-practice approach (Osborne, 2014) should also aim at increasing teachers' awareness that NGSS-aligned instruction can support science learning for *ALL* students. In addition, efforts must be made to align high-stakes standardized exams with the NGSS emphasis on conceptual understanding of disciplinary core ideas and cross-cutting concepts, rather than memorization of factual knowledge. Given that cost value has not been operationalized and studied as much as other task values (Eccles & Wigfield, 2020; Flake et al., 2015; Perez et al., 2019), additional research is needed to explore teachers' perceived barriers more deeply to implementing the science practices. Specifically, we recommend further investigation into the science practices that were associated with barriers and corresponded with low to medium levels of implementation (e.g., developing and using models).

Relationship Between Perceived Importance and Implementation

Regarding our second research question, we identified mixed findings pertaining to alignments between importance ranking and reported implementation. These findings do not align with our expectations based on the EVT, which suggests that if science teachers place higher value on certain practices, they will be more likely to implement them (Eccles, 2009). Specifically, our study showed that although the teachers valued the science practices mostly in terms of attainment value, there was not a significant relationship between the importance ranking of the top three science practices and teachers' self-reported implementation. This is not entirely surprising given that prior research has argued that science teachers' implementation of the science practices requires a sophisticated change in understanding of procedural, conceptual, and epistemic knowledge in science (Kite et al., 2021). Given this, our findings reinforce the notion that science teachers' implementation of the science practices depends not only on their value of the practices but also their knowledge and skills (Kite & Park, 2023).

These findings could be explained by the responding teachers' similarly infrequent implementation of all science practices. Stated differently, on average, teachers in this study implemented the science practices less than half of the time. Due to this, the practices that they gave lower ranks could have been correlated with their low frequency of implementation for those practices. However, practices with relatively high rankings may not have correlated with the implementation scores because teachers' reported implementations were not high enough to be distinguishable from the implementation scores of lower ranked practices. Moreover, the mismatches could be an artifact of the teachers not fully understanding the practices (Kite et al., 2021) and, thus, being unable to accurately report their implementation. Considering this, we suggest that future research combine individual or focus group interviews with survey data to further understand how factors other than teachers' perceived value, including teachers' knowledge and skills, influence their instructional decisions and implementations of the NGSS science practices in their classrooms.

As an example, contrary to previous research suggesting teachers' infrequently implement explanations (Hayes et al., 2016), teachers in our study reported implementing explanations most frequently. A plausible reason for the higher frequency of reported explanation implementation could be that teachers think of explanations in narrow terms, such as explaining a concept or describing data from a lab. In this vein, Kang et al. (2018) found that teachers accurately described students' observations as the beginning of explanation construction, but did not have a clear idea of how to move students from the initial observation to the construction of a full evidence-based explanation. If teachers in our study understood explanation construction as intrinsically integrated with other practices (NRC, 2012), we would expect that adjacent practices (e.g., data analysis or obtaining information) should have similar levels of reported implementation. This, however, was not the case.

In conclusion, teachers' values directly impact their instructional decisions. Through this study we have demonstrated that teachers' attach high attainment value to the eight NGSS science practices and that their perceived importance of a practice rarely corresponds with the frequency of their implementation of this practice. Consequently, we recommend that science teacher PD initiatives work to help teachers' develop strong utility value for each of the science practices.

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Appendix A: Science Practice Implementation (SPI) Survey Items

Table A1

Likert-Scale Survey on How Often Teachers Implement the Eight Science Practices (Park et al., 2022)

How often do students in your classroom typically...

	Never	Sometimes	About half the time	Most of the time	Always
1. develop scientific questions which guide experimental design?	☐	☐	☐	☐	☐
2. use questions to critique experimental design or scientific models?	☐	☐	☐	☐	☐
3. develop models and use them to explain scientific concepts?	☐	☐	☐	☐	☐
4. develop and revise models based on evidence to make predictions about scientific phenomena?	☐	☐	☐	☐	☐
5. use the same set of steps to reach a conclusion in a project or experiment?	☐	☐	☐	☐	☐
6. plan and conduct their own investigations to answer their own questions?	☐	☐	☐	☐	☐
7. engage in analysis (statistical processing, graphing, etc.) to make sense of data?	☐	☐	☐	☐	☐
8. consider the limitations of data collection and analysis?	☐	☐	☐	☐	☐
9. use mathematical and/or computational models to identify relationships in data?	☐	☐	☐	☐	☐
10. use mathematical and/or computational models to make and test predictions?	☐	☐	☐	☐	☐
11. make explanations based on data and current scientific understanding?	☐	☐	☐	☐	☐
12. employ a claim, supporting evidence, and connecting reasoning when constructing explanations of their findings?	☐	☐	☐	☐	☐
13. construct written and/or oral arguments based on data and evidence?	☐	☐	☐	☐	☐
14. engage in critiquing one another's scientific arguments based on evidence?	☐	☐	☐	☐	☐
15. engage in reading and evaluating scientific information from multiple authoritative sources?	☐	☐	☐	☐	☐
16. communicate scientific ideas using multiple representations (oral, graphic, textual, mathematical)?	☐	☐	☐	☐	☐

Table A2

Alignment Between Science Practices and SPI Items (Park et al., 2022)

Science Practices	**Definition/SPI Items**
Asking questions	Develop scientific questions which guide experimental design Lederman et al., 2014; NGSS Lead States, 2013b)
	Use questions to critique experimental design or scientific models (NGSS Lead States, 2013b)
Developing and using models	Develop models and use them to explain scientific concepts (NGSS Lead States, 2013b; Windschitl et al., 2008)
	Develop and revise models based on evidence to make predictions about scientific phenomena (NGSS Lead States, 2013b; Windschitl et al., 2008)
Planning and carrying out investigations	Use the same set of steps to reach a conclusion in a project or experiment (Abd-El-Khalick et al., 2008; NGSS Lead States, 2013b)
	Plan and conduct their own investigations to answer their own questions (NGSS Lead States, 2013b)
Analyzing and interpreting data	Engage in analysis (statistical processing, Graphing, etc.) to make sense of data (Leonelli, 2015; NGSS Lead States, 2013b)
	Consider the limitations of data collection and analysis (NGSS Lead States, 2013b)
Using mathematics and computational thinking	Use mathematical or computational models to identify relationships in data (NGSS Lead States, 2013b; Weintrop et al., 2016)
	Use mathematical or computational models to make and test predictions (NGSS Lead States, 2013b; Weintrop et al., 2016)
Constructing explanations	Make explanations based on data and current scientific understanding (NGSS Lead States, 2013b; Osborne et al., 2003)
	Employ a claim, supporting evidence, and connected reasoning when constructing explanations of their findings (NGSS Lead States, 2013b)
Engaging in argument from evidence	Construct written and/or oral arguments based on data and evidence (NGSS Lead States, 2013b; Sandoval & Millwood, 2007)
	Engage in critiquing one another's scientific arguments based on evidence (NGSS Lead States, 2013b)
Obtaining, evaluating, and communicating information	Engage in reading and evaluating scientific information from multiple authoritative sources (NGSS Lead States, 2013b; Osborne et al., 2003)
	Communicate scientific ideas using multiple representations (NGSS Lead States, 2013b; Osborne et al., 2003)

Appendix B: SPI Construct Validity

IRT Model: Rating Scale Model

Item	16 Items				15 Items			
	Estimate	Unweighted MNSQ	Weighted MNSQ	Alpha if Item Deleted	Estimate	Unweighted MNSQ	Weighted MNSQ	Alpha if Item Deleted
Imp01	0.255	0.84	0.90	0.922	0.248	0.93	0.97	0.926
Imp02	-0.024	0.88	0.88	0.920	-0.039	0.95	0.92	0.923
Imp03	-0.135	1.10	1.10	0.922	-0.153	1.17	1.15	0.925
Imp04	0.735	1.23	1.22	0.920	0.747	1.26	1.23	0.923
Imp05	-0.220	1.57	1.35	0.928				
Imp06	0.684	0.93	0.96	0.922	0.695	0.93	0.96	0.925
Imp07	-0.560	0.85	0.86	0.920	-0.592	0.91	0.91	0.924
Imp08	0.186	0.95	1.02	0.918	0.178	0.92	1.01	0.922
Imp09	0.012	0.97	1.01	0.919	-0.002	1.00	1.04	0.922
Imp10	0.530	1.03	1.04	0.919	0.531	1.07	1.09	0.922
Imp11	-0.977	0.83	0.80	0.919	-1.027	0.89	0.84	0.923
Imp12	-0.492	0.97	0.96	0.919	-0.525	0.94	0.96	0.922
Imp13	-0.210	0.94	0.99	0.918	-0.234	0.91	0.94	0.921
Imp14	0.587	1.07	1.05	0.920	0.589	1.06	1.05	0.923
Imp15	0.219	1.05	1.12	0.922	0.209	1.09	1.16	0.926
Imp16	-0.590	0.92	0.86	0.918	-0.627	0.91	0.86	0.921
Separation Reliability	0.945				0.950			
EAP/PV RELIABILITY	0.912				0.924			
Cronbach's alpha	0.925				0.928			
Chi-square test of parameter equality	251.050				255.03			
df	15				14			
p	0.000				0.000			
Final Deviance	4740.37207				4394.08532			
Akaike Information Criterion (AIC)	4780.37207				4432.08532			
Akaike Information Criterion Corrected (AICc)	4775.202				4427.40039			
Bayesian Information Criterion (BIC)	4837.41267				4486.2739			
Parameter Estimated	20				19			

Appendix C: EVT (Wigfield & Eccles; 2000) Coding Frame

Categories (*n*)	**Sub-Category (*n*)**	**Codes**	**Frequency**	**Percent**
Attainment (198)	Enhancing conceptual understanding (73)	Building understanding	31	10.88
		Increasing depth of understanding	24	8.42
		Connecting concepts	7	2.46
		Personalized instruction	6	2.11
		Make student thinking visible	5	1.75
	Engaging in practices of science (54)	Communicating findings	15	5.26
		Using evidence to support claims	12	4.21
		Forming conclusions	9	3.16
		Analyzing data	5	1.75
		Evaluating ideas	5	1.75
		Learning to conduct investigations	5	1.75
		Constructing explanations	3	1.05
	Developing student thinking skills (39)	Developing critical thinking	21	7.37
		Promoting creativity/Thinking outside the box	7	2.46
		Benefiting from multiple perspectives	7	2.46
		Metacognition	4	1.40
	Understanding the nature of science (32)	Questions are fundamental to science	18	6.32
		Understanding the scientific method	8	2.81
		Science practices are the foundation of science	6	2.11
Interest (57)	Enhancing student interest (36)	Engaging students	17	5.96
		Piquing student curiosity	11	3.86
		Providing hands-on learning	8	2.81
	Building student motivation (21)	Giving students ownership	13	4.56
		Student-centered teaching	8	2.81
Utility (18)	Building transferable skills (18)	Transferable skills	18	6.32
Cost/Barriers (12)	Teachers' perceptions of students (8)	Low-level students	5	1.75
		Perceived area of struggle	3	1.05
	Standards and testing (4)	Standards and testing	4	1.40

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Effects of Informal versus School-Based Field Experience on Elementary Preservice Teachers' Self-Efficacy for Teaching Science

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ABSTRACT

Prior to the fall semester of 2017, the elementary preservice teachers who were enrolled in a science methods course engaged in a variety of field experiences across different settings, mostly informal. Beginning in the fall semester of 2017, students enrolled in this science methods course completed their field experience in formalized classroom settings. Most students were placed at the site of a partnership school, a K-8 building in the local urban school district where an automated greenhouse was built. At the outset, the original study aimed to compare the self-efficacy for science teaching of the elementary education preservice teachers pre- and post-greenhouse implementation. However, the construction of the greenhouse was delayed and thus accidentally created a third cohort of students in addition to pre- and post-greenhouse. This third cohort of students were placed in a K-8 school setting but did not have access to the greenhouse. This paper compares the first two cohorts of preservice teachers, those who completed informal field experiences, and those who completed school-based field experiences without the utilization of the greenhouse.

Keywords: science education, preservice teachers, elementary science, field experience

Introduction

Science, technology, engineering, and math (STEM) fields are an ever-growing part of today's workforce (Casey, 2012). However, STEM education in K-12 schools has been sparse (National Research Council, 2012). To increase the number of college graduates in the STEM fields, K-12 schools must engage students in STEM from a young age. Unfortunately, this does not happen to the extent necessary, particularly in elementary schools. This is largely due to the fact that many elementary teachers have low self-efficacy for teaching science.

Ashton and Webb (1986) built on Bandura's (1977) idea of self-efficacy by adding two types of self-efficacy for teaching that then were expanded to content specific areas. In science, these two types are personal science teaching efficacy (PSTE) and science teaching outcome expectancy (STOE). PSTE is the teachers' belief that they can effectively teach science. STOE is the idea that effective teaching will positively impact K-12 student learning (Bursal, 2012). Prior research has determined that a large percentage of elementary teachers (both preservice and inservice) have low science teaching self-efficacy of both types (Bursal, 2012). This low self-efficacy has been linked to heightened anxiety about, and negative attitudes towards, science (Bursal, 2012; Ramey-Gassert & Shroyer, 1992). High levels of science anxiety and feelings of low self-efficacy cause elementary teachers to avoid teaching science in K-8 classrooms (Bursal, 2012). In today's fast-moving world of STEM innovation, avoidance of science is detrimental to elementary student populations.

In 2015, an Engineering faculty member at Pennsylvania Collegiate Institute (PCI, pseudonym used) approached a faculty member in the Education department about a potential collaboration. PCI is a mid-sized liberal arts college in the south central section of the state. The proposal was that the Engineering students would design and build an automated greenhouse at a local elementary school that the Education students (preservice teachers) would then utilize to implement science lessons.

Dorchester Elementary (pseudonym used) is one of eight elementary schools in the local, urban school district that borders PCI. The majority of the students who attend the school are of African American or Hispanic descent, many are English language learners, and nearly all qualify for free/reduced lunch. The district where Dorchester resides often ranks as one of the lowest in the state. Dorchester was chosen as the specific school to place the greenhouse because of its 10,000 square-foot garden space enclosed within an interior courtyard.

The greenhouse project had several goals, and while the details of those goals are beyond the scope of this work (Forsyth & Hesson, 2017) may be consulted for more information. Yet, unfortunately, the greenhouse build ran into a multitude of challenges, all of which are described in Meah et al., 2021. The initial research study aimed to compare the self-efficacy of two cohorts of elementary preservice teachers: pre- and post-greenhouse utilization. Due to the challenges encountered in building the greenhouse structure (and an unforeseen global pandemic), a third cohort of preservice teachers was accidentally created. While the creation of the greenhouse was the impetus for this project, this paper will focus on the comparison of preservice teachers who completed informal field experiences to those who completed school-based field experiences.

Research has found that there are ways to increase self-efficacy for teaching science among elementary science preservice teachers. However, it is important to note that science anxiety, attitudes, and self-efficacy are all linked. Increasing positive attitudes toward science and/or reducing anxiety around science content have been shown to increase self-efficacy for teaching science (Ramey-Gassert & Shroyer, 1992). Attempts to grow positive attitudes, increase self-efficacy, and reduce anxiety should occur in teacher preparation courses. Science methods courses that utilize hands-on inquiry approaches and firsthand teaching experiences appear to be the best at increasing preservice teacher self-efficacy (Bursal, 2012). Positive student teaching experiences implementing science lessons have also been shown to reduce anxiety around teaching science (West, 1993). Moreover, prior research supports the idea that providing preservice teachers with real-world contexts for teaching science increases their self-efficacy (Kazempour, 2018; Novak & Wisdom, 2018; Valente et al., 2018; Yu & Bethel, 1991). Generally, previous research demonstrates that teacher educators need to use methods courses to help preservice teachers reduce anxiety and develop positive attitudes toward science. This will lead to increased science teaching self-efficacy.

Research Study Questions

All elementary education (PK-4) majors at PCI must successfully complete a science methods course, ECH 330: Teaching Science at the Early Childhood Level. This course has a 20-hour field experience requirement. Prior to the fall semester of 2017, the preservice teachers enrolled in this course completed their field experience hours in a variety of settings, mostly engaging in informal science instruction. One component required students to attend a volunteer training for the nature center at a local state park and then assist a group of students on a field trip. A second component involved delivering a lesson designed by a national program. Some of these programs took place in classroom settings, some took place in after school settings, and some took place at the local branch of the county library. The field experience activities were haphazard and not consistent among preservice teachers, even in the same methods class. This group is labeled Cohort A (informal field experience).

The lead author inherited the ECH 330 course during the fall 2017 semester following a colleague's retirement. While the course continued to utilize a hands-on inquiry approach, the author added the component of an authentic classroom experience that did not exist before. After the fall 2017 semester, all preservice teachers enrolled in ECH 330 completed their field experience hours in formalized classroom settings. During these school-based field experiences, preservice teachers engaged in more typical field experience activities, such as working with students in small groups, connecting science to literature, and teaching at least one whole-group lesson. Preservice teachers were required to spend at least six hours in the field every week for 12 weeks. The details of how the classroom placements were made in the subsequent four semesters are described in the methods section below. This group is labeled Cohort B (formal field experience).

According to prior research, the utilization of the garden at Dorchester, in conjunction with hands-on inquiry-based pedagogies in the science methods course and formalized, authentic field experiences in K-4 classrooms, should result in higher PSTE and STOE for preservice elementary teachers. Therefore, this paper asks three questions:

1. Does the type of field experience placement, formal or informal, have an impact on overall self-efficacy for teaching science among elementary preservice teachers?
2. Does the type of field experience placement, formal or informal, have an impact on self-efficacy for teaching science among elementary preservice teachers in two sub-categories: PSTE and STOE?
3. What role does the type of field experience placement, formal or informal, have on elementary preservice teachers' perceptions about their self-efficacy for teaching science?

Methods

All participants were preservice teachers at PCI. Starting in the fall 2017 semester, preservice teachers enrolled in ECH 330 completed their field experience hours in classroom settings. Under the assumption that the greenhouse would be operational by fall 2017, the education department began placing students in ECH 330 at the partnership school, Dorchester Elementary, during this time. If preservice teachers were not placed at Dorchester, every effort was made to place them in the same urban district. However, not all students enrolled in the course were placed at Dorchester, nor in the urban district, and there were a number of reasons for this. In the spring semester of 2018, there was a miscommunication between the Field Services Division at PCI and the local urban district when it came to placements. At times, Dorchester could not support all of students enrolled in ECH 330. Alternatively, some elementary preservice teachers arranged to transition from their field experience directly into student teaching, typically in more suburban districts. Lastly, sometimes the preservice teachers were co-enrolled in courses that required field experience that was difficult to complete at Dorchester and so were given different placements. Nearly all students completed their field experience hours in a PK-4th grade classroom. In certain cases, some students were placed in a 5/6th grade classroom, and most of these students were obtaining a dual elementary/special education certification. The special education certification in this state certifies students up to 8th grade, so most preservice teachers were within their certification band. In the fall of 2017, one student enrolled in ECH 330 was earning a middle level certification (grades 4-8), and so she was placed in a 5/6th grade classroom. Table 1 shows the breakdown of student placements by semester.

Table 1

Student Field Experience Placements by Semester

Semester	Enrolled in ECH 330	Dorchester	Urban, but not Dorchester	Outside Urban District	Above 4th grade (5/6)
Fall 2017	26	23	2	1	3 (2 dual SPED, 1 MLE)
Spring 2018	26	2	4	20	2 (both dual SPED)
Fall 2018	17	12	2	3	2 (1 dual SPED)
Spring 2019	12	7	5	0	1 (dual SPED)

Beginning in the fall semester of 2016, students enrolled in ECH 330 were asked to participate in the current research study. At the start of each semester, students who volunteered to participate were asked to sign an informed consent form and complete the Science Teaching Efficacy Belief Instrument (STEBI-B), a measure of self-efficacy for teaching science in preservice elementary teachers (Bleicher, 2004). Initially designed by Enochs and Riggs (1990), Bleicher (2004) edited the instrument to revise or remove items that were found non-reliable, thus making the overall instrument more valid for use with preservice teachers. A copy of the STEBI-B can be found in the methods supplement. The same participants were asked to complete the STEBI-B at the end of the semester as well. The STEBI-B was administered by the lead author every semester. Students were instructed to use the same alphanumeric code for both the pre- and post-test so that their data would be anonymous but still trackable for comparison. Data was compared using the SPSS Statistics program.

Additionally, a subset of participants each semester were invited to join a focus group to discuss their field experience placements. Initial focus groups were conducted by the lead author on this paper. Later focus groups were conducted by a student research assistant who was unaffiliated with the class, since the lead author was the professor for ECH 330. The questions asked during the focus group are available as supplementary material accompanying the online article. Focus groups were recorded and transcribed, with most transcriptions completed through a service, but two were transcribed by a student research assistant. There were two supplementary pieces of qualitative data collected as well. In the fall 2017 semester, students were asked to volunteer to submit responses to a set of questions about their experience at urban placements. Fourteen students opted to complete this assignment. This list of questions is available as supplementary material accompanying the online article. In the spring semester of 2019, some students made mention of their experiences at Dorchester as a part of an unrelated assignment. These students granted permission to use their comments as part of this study. Qualitative data was coded for patterns by the lead author on this paper. Table 2 shows the participants who completed the STEBI-B and joined the focus group by semester.

Table 2

STEBI-B and Focus Group Participants by Semester

Semester	STEBI-B *n*	Focus Group *n*
Fall 2016 – Cohort A	24	6
Spring 2017 – Cohort A	15	4
Fall 2017 – Cohort B	26	6
Spring 2018 – Cohort B	24	5
Fall 2018 – Cohort B	9	8
Spring 2019 – Cohort B	12	5
TOTAL Cohort A	**39**	**10**
TOTAL Cohort B	**71**	**24**
OVERALL TOTAL	**110**	**34**

Cohort A includes those students who completed their field experience hours for ECH 330 at informal settings. Cohort B includes those students who completed their field experience hours for ECH 330 in formalized classroom settings.

Results

Impact on Overall Self-Efficacy

The first question researchers sought to answer was: Does the type of field experience placement, formal or informal, have an impact on overall self-efficacy for teaching science among elementary preservice teachers? This question was addressed by comparing the difference in means of the pre- and post-STEBI-B results overall for Cohorts A and B. Descriptive data summarizing these results are displayed in Table 3.

Table 3

Average Difference in Overall Means for Cohorts A and B

Measure	n	Mean
Cohort A	39	0.229
Cohort B	71	0.402

An independent samples *t*-test was employed to determine the existence of a statistically significant difference between Cohort A and Cohort B STEBI-B scores. The null hypothesis for this independent samples *t*-test was that there was no difference in the mean STEBI-B scores of Cohort A and Cohort B. The independent samples *t*-test indicated a *p* value of 0.002. This value is below the $p = 0.05$ threshold indicating the null hypothesis was rejected. The results of the independent-sample *t*-test indicated that the mean scores for Cohorts A and B were significantly different, with Cohort B reporting higher self-efficacy for teaching science than Cohort A. Table 4 presents the results of this independent samples *t*-test.

Table 4

Independent-Sample t-test Comparing Overall Scores for Cohorts A and B

	df	MD	t	p
Cohorts A + B Overall Scores	108	-0.174	-3.215	0.002

Data collected from the beginning (pre) and end of course (post) administration of the STEBI-B were compared to answer research question one. Results for Cohorts A and B combined are displayed in Table 5. The null hypothesis for the paired sample *t*-test, employed to determine if there was a statistically significant difference between participants' self-efficacy for teaching science prior to completing ECH 330 (pre) and after completing ECH 330 (post), indicated that there was no difference between the mean scores for the pre and post-STEBI-B samples, either overall or on either subscale.

The paired samples *t*-test indicated a p value less than 0.00 on all three measures. These values are below the $p = 0.05$ threshold, indicating a rejection of the null hypothesis. The results of the paired samples *t*-test on all three measures demonstrated that post-STEBI-B scores were significantly higher than pre-STEBI-B scores. The results are illustrated in Table 6.

Table 5

Combined Pre- and Post-Course STEBI-B Overall and Subscale Results

Measure	n	Mean	SD
Overall Pre	110	3.673	0.291
Overall Post	110	4.014	0.345
PSTE Pre	110	3.804	0.332
PSTE Pre	110	4.260	0.367
STOE Pre	110	3.495	0.431
STOE Post	110	3.669	0.478

Table 6

Paired Sample t-test Comparison of Pre- and Post-Course Overall and Subscale Scores

Measure	df	Mean	SD	t	p
Overall Pre-Post	109	-0.341	0.282	-12.660	0.000
PSTE Pre-Post	109	-0.455	0.325	-14.684	0.000
STOE Pre-Post	109	-0.173	0.446	-4.076	0.000

Impact on Subcategories of Self-Efficacy (PSTE & STOE)

The second question researchers sought to answer was: Does the type of field experience placement, formal or informal, have an impact on self-efficacy for teaching science among elementary preservice teachers in two sub-categories: PSTE and STOE? This question was addressed by comparing the difference in means of the pre- and post-STEBI-B results for subsets of questions on the STEBI-B as defined by Bleicher (2004). PSTE was measured by questions 2, 3, 5, 6, 8, 12, 17, 19, 20, 21, 22, and 23. STOE was measured by questions 1, 4, 7, 9, 10, 11, 13, 14, 15, and 16. Descriptive data summarizing these results are displayed in Table 7.

Table 7

Average Difference in PSTE and STOE Means for Cohorts A and B

Measure	n	PSTE Mean	STOE Mean
Cohort A	39	0.318	0.087
Cohort B	71	0.531	0.221

An independent samples *t*-test was employed to determine the existence of a statistically significant difference between the Cohort A and Cohort B subscale scores. The null hypothesis for this independent samples *t*-test was that there was no difference in the mean subscale scores of Cohort A and Cohort B. For the PSTE subscale, the independent samples *t*-test indicated a *p* value of 0.001. This value is below the $p = 0.05$ threshold indicating the null hypothesis was rejected. The results of the independent-sample *t*-test indicated that the mean scores for Cohorts A and B were significantly different, with Cohort B reporting a higher personal science teaching efficacy belief than Cohort A. For the STOE subscale, the independent samples *t*-test indicated a *p* value of 0.133. This value is above the p = 0.05 threshold indicating the null hypothesis was accepted. The results of the independent-sample t-test indicated that the mean scores for Cohorts A and B were not significantly different on the subscale of science teaching outcome expectancy. Table 8 presents the results of this independent samples t-test.

Table 8

Independent-Sample t-test Comparing Subscale Scores for Cohorts A and B

	df	**MD**	**t**	**p**
PSTE	108	-0.213	-3.449	0.001
STOE	108	-0.134	-1.515	0.133

Data collected from the beginning (pre) and end of course (post) administration of the STEBI-B were compared to answer research question one. Disaggregated results for Cohorts A and B are displayed in Table 9.

Table 9

Disaggregated Pre- and Post-Course STEBI-B Overall and Subscale Results

		Cohort A			**Cohort B**	
Measure	**n**	**Mean**	**SD**	**n**	**Mean**	**SD**
Overall Pre	39	3.744	0.306	71	3.634	0.277
Overall Post	39	3.972	0.383	71	4.037	0.322
PSTE Pre	39	3.903	0.399	71	3.750	0.277
PSTE Pre	39	4.220	0.420	71	4.281	0.335
STOE Pre	39	3.538	0.458	71	3.472	0.417
STOE Post	39	3.625	0.536	71	3.693	0.445

The null hypothesis for the paired sample t-test, was employed to determine if there was a statistically significant difference between participants' self-efficacy for teaching science prior to completing ECH 330 (pre) and after completing ECH 330 (post). Results from this study indicated that there was no difference between the mean scores for the pre- and post-STEBI-B samples, either overall or on either subscale. For Cohort A, the paired samples t-test indicated a p value less than 0.00 on the overall score and the STOE subscale score. These values are below the p = 0.05 threshold, indicating a rejection of the null hypothesis. The results of the paired samples t-test on these two measures for Cohort A demonstrated that post-STEBI-B scores were significantly higher than pre-STEBI-B scores. For Cohort A's PSTE, the paired samples t-test indicated a p value of 0.344. This value is above the p = 0.05 threshold, indicating an acceptance of the null hypothesis. The pre-test PSTE subscale scores for Cohort A were not significantly different than post-test scores.

The paired samples t-test indicated a p value less than 0.00 on all three measures for Cohort B. These values are below the p = 0.05 threshold, indicating a rejection of the null hypothesis. The results of the paired samples t-test on all three measures for Cohort B demonstrated that post-STEBI-B scores were significantly higher than pre-STEBI-B scores. The results described above are illustrated in Table 10.

Table 10

Paired Sample t-test Comparison of Cohort Specific Pre and Post-course Overall and Subscale Scores

		Cohort A			
Measure	**df**	**Mean**	**SD**	**t**	**p**
Overall Pre-Post	38	-0.229	0.283	-5.041	0.000
PSTE Pre-Post	38	-0.318	0.348	-5.706	0.344
STOE Pre-Post	38	-0.086	0.561	-0.958	0.000

		Cohort B			
Measure	**df**	**Mean**	**SD**	**t**	**p**
Overall Pre-Post	70	-0.402	0.264	-12.842	0.000
PSTE Pre-Post	70	-0.531	0.288	-15.555	0.000
STOE Pre-Post	70	-0.221	0.363	-5.128	0.000

Impact on Perceptions of Self-Efficacy

Lastly, the researchers wanted to answer the question: What role does the type of field experience placement, formal or informal, have on elementary preservice teachers' perceptions about their self-efficacy for teaching science? This question was answered qualitatively with focus group interviews and student writing samples. Questions for the focus group and writing samples can be found in the Methods Supplement for this paper. Our student researcher and the lead author on this paper utilized open coding to find patterns in the data. These patterns are described below.

Students in Cohort A felt that the informal settings were beneficial to observe and work with students in a variety of settings but did not believe the informal settings assisted their transition into a classroom. As one student noted "Even though I felt like I could take my kids outside and do a lot of extension activities…I didn't feel like I had that classroom experience to help boost my confidence in teaching a classroom science lesson." Another student noted that she wished she had spent more time "in a classroom teaching science" as opposed to informal settings because "it's just not beneficial to what we're going to be doing in our future." She went on to explain that field trips are becoming less and less frequent in the classroom and the informal settings seemed to be a mismatch. A third student stated that although she may have had bad experiences in previous school-based placements, she "still had an understanding of what [she] need[ed] to do for the grade" she might be teaching and she knew what she should be "reaching towards." She didn't feel the informal placements offered much value at all. These students felt that the informal settings lacked a future-looking attitude.

The Cohort A students' perceived low-self efficacy for teaching science could be related to the fact that many reported not writing or delivering their own science lessons in a classroom. Even students who spent some of their field placement time in a K-4 classroom did not feel confident in their ability to teach science. Some schools taught science very infrequently and it was difficult for the preservice teachers to plan to be present during science instruction. One student felt she was "kinda left in the dark on how to write [her] science lesson and what was gonna work with the kids." Others felt semi-confident in their ability with the grade where they were placed, but not with different grades. According to one student "I don't really feel necessarily confident in teaching a third or fourth-grade science lesson….because I've never had to write one or implement one." There was one informal setting that was perceived to be the most beneficial – placements with Leap into Science. More commonly referred to as Leap, this nationwide program "integrates open-ended science activities with children's books for young children and their families" (Franklin Institute, 2018). Students applauded this program because they were able to teach a lesson on their own "from start to finish." Another student added "we had that whole hour just for us, the teachers didn't chime in at all." The common experience that contributed positively to self-efficacy for teaching science was time spent developing and implementing their own lessons.

Cohort A thought the hands-on modeling of science teaching by the course professor was valuable, but again felt unable to translate this into teaching science in an elementary classroom. Several mentioned their ability to incorporate children's literature into a lesson and demonstrate hands-on activities, but one student commented: "some of the activities weren't always as realistic as what they would be in a classroom setting." Another student stated: "I know what inquiry based science is but I don't know how to implement it into my classroom." A third student added

> But I think realistically as a teacher you are going to have curriculum that you need to follow… I just feel like the whole semester being about inquiry based science was one, redundant, and two, not completely realistic. I just felt like there could have been a better balance with, I don't know, just some real stuff (Personal communication, May 9, 2017).

Students were taught about the 5E instructional model but lamented the lack of connection to "actual standards". At least two students stated that they would have liked to see a "better balance" between the hands-on component, the 5E model, and the science standards.

Another factor that negatively affected the confidence of Cohort A students was a lack of science content review in the methods course. While they felt confident in teaching generally, several noted that their confidence in science was "knock[ed] down" because they did not feel like they "learned anything about concepts, only about the approach to the concepts." One admitted to picking the "easiest" topic she could "instead of challenging [herself]" when she taught a short lesson because she was so uncomfortable with science content. Another reported feeling "at a loss in way" because she did not perceive any connection between the hands-on activities and science content that would be taught in a K-4 classroom. One student who taught a lesson through Leap into Science stated

> I was in a third grade classroom and at the time that we were going in they were in a matter unit and it was embarrassing how little I knew … My thoughts were how do you teach those science concepts when you don't understand them. Sure you might be the greatest teacher and you might have really good openers and closers and use the 5E model but just because you know how doesn't mean you know the content enough so I definitely don't feel prepared. I feel like I know how to approach science, but I don't think I would be confident in the science concept at hand. I would have to do a lot of outside research before I felt comfortable teaching it to my students (Personal communication, May 9, 2017).

The perceived lack of personal content knowledge combined with the perceived failure of science content review in the methods course caused many Cohort A students to feel a lowered sense of self-efficacy for teaching science.

Students in Cohort B agreed with students in Cohort A on some aspects. Cohort B had a different professor than Cohort A, but Cohort B agreed that the hands-on modeling by their course professor was valuable. In addition to hands-on activities, Cohort B also mentioned modeling of other pedagogies like extended wait time, flexible assignments and due dates, and questioning techniques. Other pedagogies were rarely mentioned by Cohort A. Cohort B agreed that there was "not really a lot of science" being taught in schools. They mentioned a stronger emphasis on mathematics and reading, which echoed sentiments by students in Cohort A.

Comments from Cohort B differed from Cohort A in three specific ways that impacted Cohort B's collective self-efficacy for teaching science. First, they reported more practice in lesson planning. Second, they received more review of elementary science content. Lastly, they were able to build relationships with their host teachers in the field placement classrooms as they delivered lessons to K-8th grade students. Each of these will be described in more detail.

Cohort A rarely implemented formal lessons, but when they did, the lessons were scripted. On the other hand, students in Cohort B had to create at least three distinct science lessons using the 5E lesson plan format, and they had to deliver at least one of those lessons. One of the required lessons was designed to be shorter in scope so that all lessons could be shared with peers in the class. According to one student, it helped him better understand the 5E format.

> I thought that the simplicity of it and the fact that we only had to really come up with the lesson as opposed to making materials and stuff, helped me focus on the scope and sequence of the lesson itself and come to an understanding of why it's structured the way it's structured, and being able to watch that reflected through how you taught your lessons in your class was beneficial. Because it kinda helps you focus on, like I said, it helps you focus on the structure of the lesson, you get less caught up in how pretty your stuff looks, and more focused on the sequence of it and stuff, and how you're supposed to introduce the content, and how you're supposed to distribute materials (Personal communication, December 2018).

Other students shared this sentiment as well. Several students also commented on the fact that the lessons were shared so the "book of science lessons…formatted in the 5Es already [would be] useful as a resource for us in the future." Cohort B shared many positive comments about the 5E lesson planning format and how the professor in the methods class modeled it. Although it was new to the students, they reported that planning and implementing lessons in this way was a valuable exercise. As one student said, "I know it was new to me and probably to everyone else too, so actually implementing that helped out a lot in understanding it more." Several students conveyed that utilization of the 5E model made it easier to incorporate what the Next Generation Science Standards (NGSS) refers to as Science and Engineering Practices (National Research Council, 2012). Science and engineering practices are those skills that transcend a science classroom like asking questions, using models, communicating information, and interpreting data. Cohort B also commented on the assignment that required them to plan a 5E lesson that connected to a field trip. While students thought it was a difficult assignment, they thought it was useful to think about all the behind-the-scenes aspects that go into planning a successful field trip. According to one, "this [was] the only time we've been taught how to prepare for a field trip, and I just thought that was a good tool to have."

Unlike Cohort A, Cohort B believed they received a lot of content review in their methods course. The professor for the methods course often had students plan lessons in groups. Students stated, "once we shared out…we did get multiple ideas for the same science topic, but different ways that we could go about teaching it for different grade levels." Lesson planning around a specific topic served as a content refresher for many students and they were able to take the ideas they got from their peers into their field placement classroom. Furthermore, students in the second half of Cohort B were required to take a science content course that covered concepts specialized for K-8th grade preservice teachers. Students in the first half of Cohort B suggested that such a course would be a good idea and students in the second half agreed. One student stated: "I think the concepts course helped prepare me for teaching science, because a lot of stuff that we may have forgotten over the years were reviewed [there], so that helped me teach science better." A second student agreed, "some of us didn't have to take science concepts, so that put us at a slight disadvantage for some of our content teaching." Another connected her experience in the science concepts course to the methods course saying, "the science concepts course helped me get back the knowledge that I sort of lost from elementary science but then the teaching science course really helped us actually create those science lesson plans." One student even said, "I was the least amount of nervous teaching my science lessons as I ever felt teaching a lesson" and she attributed this confidence to activities that had been done in the methods course. The addition of the science concepts course and extra content review in the methods course contributed positively to self-efficacy for teaching science.

For Cohort B, the factor that appeared to have the biggest positive impact on self-efficacy for teaching science was the actual experience in a K-8th grade classroom. Students in Cohort B made statements as follows

> I was never good at science either growing up or like in school, but after having this positive experience and learning so much throughout the semester, just like thinking about teaching science in the future doesn't really make me nervous and I feel like I have an abundance, a plethora, of resources to use. … I feel prepared to teach it in the future. (Personal communication, Spring 2018).

Two students commented that they had initially been nervous about being placed in a fourth grade classroom but felt much more confident in their ability to teach science after successfully teaching a lesson in an upper-elementary classroom. Other students referenced Cohort A's placements in informal settings, stating that such placements "would be a good testament to how it is to teach science in the classroom" because informal settings are designed to be engaging. Therefore, teachers do not need to "go the extra mile to put out that engagement factor" nor do they have to worry about classroom management. Many students in Cohort B discussed the relationships they had built with their field placement host teachers over the course of the semester. Several discussed the level of feedback they received, with one student stating that the in-depth feedback from the host teacher reaffirmed that, "she was grading [her] honestly" and she "really knew that [the host teacher] cared." The positive experiences in the classroom, both delivering lessons and interacting with in-service host teachers, contributed to the higher levels of self-confidence among the preservice teachers in Cohort B.

Discussion

Bursal (2012) found that science methods courses that utilize hands-on inquiry increase teacher self-efficacy. Data from this study support this finding. Although taught by different professors, both Cohort A and Cohort B were enrolled in a science methods course that employed a hands-on, inquiry model of teaching. When data for both cohorts was combined, there was a highly significant increase in overall self-efficacy for teaching science. Data also show a highly significant increase on both subscales of the STEBI-B, PSTE, and STOE. Cohort B demonstrated significant growth overall and in both subscales between pre- and post-test scores. Although Cohort A showed an increase in overall self-efficacy and STOE, Cohort A did not show a significant difference in PSTE between pre- and post-tests. For Cohort A, it seems the course and its accompanying informal field experiences did not have an effect on the preservice teachers' belief that they could effectively teach science. Cohort B completed field experience in formal classroom settings, whereas Cohort A completed their field experience in informal science settings. The biggest difference between Cohort A and Cohort B was the type of field placement setting. Combining the qualitative data with the quantitative data, the formal classroom experience of Cohort B appears to have had the most significant impact on overall self-efficacy and both sub-scales. Several studies have found that providing preservice teachers with firsthand experiences and real-world contexts for teaching science reduces anxiety around teaching science and increases self-efficacy for teaching science (Bursal, 2012; Kazempour, 2018; Novak & Wisdom, 2018; Valente et al., 2018, West, 1993 Yu & Bethel, 1991). Data from this study support these findings.

While a combined analysis of cohorts showed an increase in self-efficacy for teaching science, there was a difference between the two cohorts when their STEBI-B scores were compared. On overall self-efficacy for teaching science, the data show that Cohort B reported higher self-efficacy than Cohort A. When subscale scores for Cohorts A and B were compared, Cohort B reported a higher PSTE than Cohort A. However, there was no statistical difference between Cohorts A and B on the STOE subscale. STOE is the idea that effective teaching positively impacts K-12 student learning. Although Cohort B felt they were better able to effectively teach science (as measured by the PSTE subscale and reinforced through qualitative data), neither cohort felt that they would positively affect student learning. Comments about STOE did not appear in any comments by participants in the focus groups. In future semesters, a targeted question to solicit perceptions on STOE will be added to focus group interviews.

The addition of the science concepts class increased knowledge content confidence, which in turn increased Cohort B's self-efficacy for teaching science. Field experience placement in a classroom setting had a positive impact on preservice teachers' belief that they could effectively teach science. This was true for all participants in Cohort B and those few students in Cohort A who were able to teach a classroom-based lesson. The extra practice of planning and delivering their own lessons to K-8th grade students in a formalized setting served to increase their confidence. The informal settings did not increase confidence for preservice teachers in the same way, partially because the lessons were standardized. The actions of "being a teacher" – researching the content, writing a coherent lesson, and then delivering that lesson – were perceived by the participants as the best preparation for science teaching, and thus positively impacted their perception about their self-efficacy for teaching science.

Future Research

At the outset of the project, the study aimed to compare the self-efficacy for science teaching of the elementary education preservice teachers pre- and post-greenhouse implementation. However, the construction of the greenhouse was delayed and thus accidentally created a third cohort of students in addition to pre- and post-greenhouse. This study compared those preservice teachers who completed their field experience hours for ECH 330 at informal settings (pre-greenhouse) to those who completed their field experience hours in a K-8th grade school setting, but without access to the greenhouse. The greenhouse construction and automation was completed in August of 2019. Data collection began in spring 2020, but no post-treatment data was collected because of the global pandemic. The pause in data collection continued in the fall 2020 and the entire 2021-2022 academic year. The final phase of this project will be underway beginning in fall 2022 now that preservice teachers enrolled in ECH 330 can utilize the greenhouse as intended. Future research will compare three cohorts of preservice teachers: those who completed informal field experiences, those who completed formal field experiences without use of the greenhouse, and those who completed formal field experiences with the use of the greenhouse. The addition of the greenhouse will further increase the hands-on inquiry experiences and real-world contexts for our preservice teachers. This should increase the self-efficacy for preservice teachers even more. The lead author intends to resume data collection in fall 2023 for at least four subsequent semesters. This additional data will be compared to data presented in this study. It is the hope that a comparison of the three phases of the education piece of this project will continue to show an increase in self-efficacy for teaching science among elementary preservice teachers.

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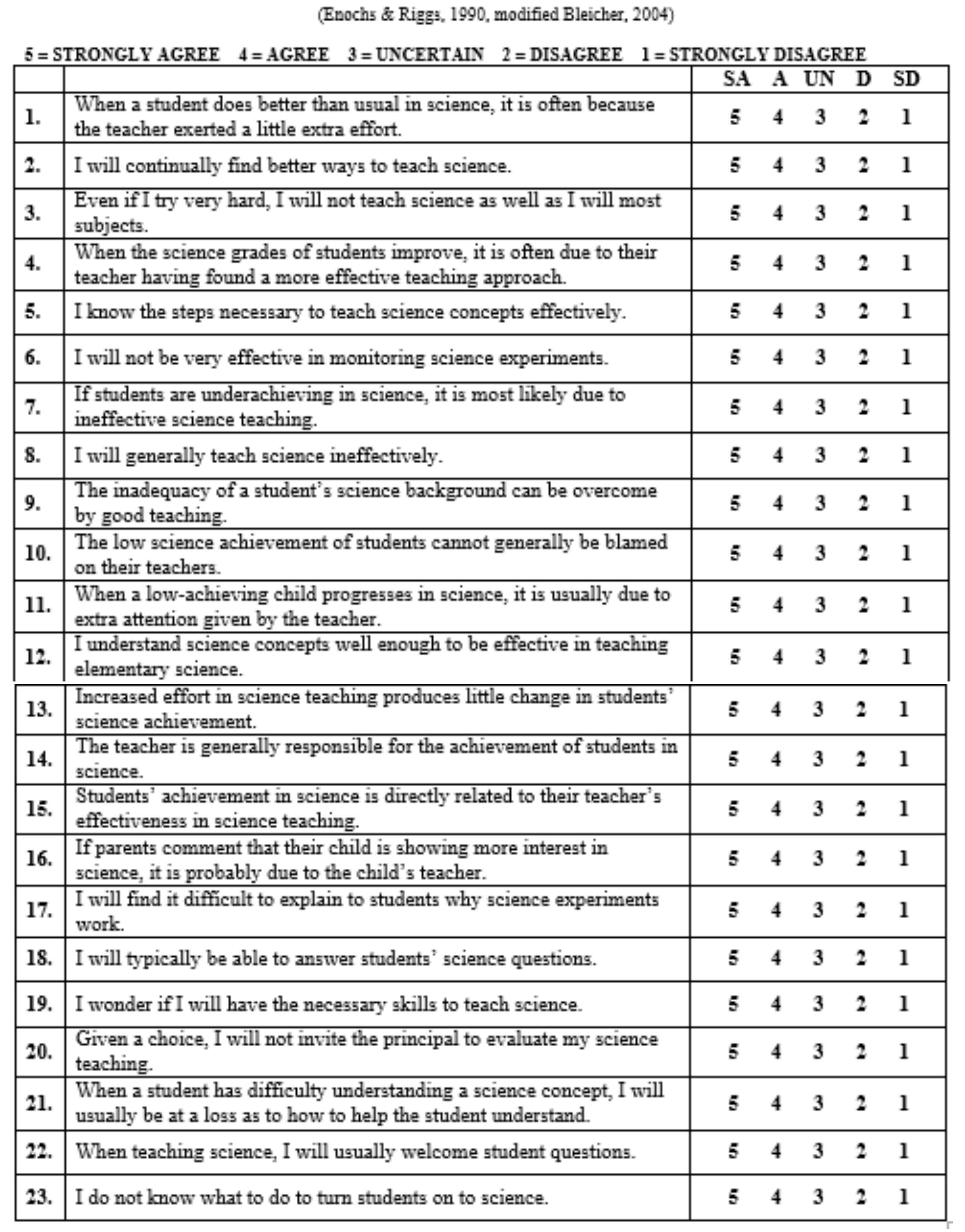
Appendix A

STEBI-B Survey Instrument



(Enochs & Riggs, 1990, modified Bleicher, 2004)

5 = STRONGLY AGREE 4 = AGREE 3 = UNCERTAIN 2 = DISAGREE 1 = STRONGLY DISAGREE

		SA	A	UN	D	SD
1.	When a student does better than usual in science, it is often because the teacher exerted a little extra effort.	5	4	3	2	1
2.	I will continually find better ways to teach science.	5	4	3	2	1
3.	Even if I try very hard, I will not teach science as well as I will most subjects.	5	4	3	2	1
4.	When the science grades of students improve, it is often due to their teacher having found a more effective teaching approach.	5	4	3	2	1
5.	I know the steps necessary to teach science concepts effectively.	5	4	3	2	1
6.	I will not be very effective in monitoring science experiments.	5	4	3	2	1
7.	If students are underachieving in science, it is most likely due to ineffective science teaching.	5	4	3	2	1
8.	I will generally teach science ineffectively.	5	4	3	2	1
9.	The inadequacy of a student's science background can be overcome by good teaching.	5	4	3	2	1
10.	The low science achievement of students cannot generally be blamed on their teachers.	5	4	3	2	1
11.	When a low-achieving child progresses in science, it is usually due to extra attention given by the teacher.	5	4	3	2	1
12.	I understand science concepts well enough to be effective in teaching elementary science.	5	4	3	2	1
13.	Increased effort in science teaching produces little change in students' science achievement.	5	4	3	2	1
14.	The teacher is generally responsible for the achievement of students in science.	5	4	3	2	1
15.	Students' achievement in science is directly related to their teacher's effectiveness in science teaching.	5	4	3	2	1
16.	If parents comment that their child is showing more interest in science, it is probably due to the child's teacher.	5	4	3	2	1
17.	I will find it difficult to explain to students why science experiments work.	5	4	3	2	1
18.	I will typically be able to answer students' science questions.	5	4	3	2	1
19.	I wonder if I will have the necessary skills to teach science.	5	4	3	2	1
20.	Given a choice, I will not invite the principal to evaluate my science teaching.	5	4	3	2	1
21.	When a student has difficulty understanding a science concept, I will usually be at a loss as to how to help the student understand.	5	4	3	2	1
22.	When teaching science, I will usually welcome student questions.	5	4	3	2	1
23.	I do not know what to do to turn students on to science.	5	4	3	2	1

Appendix B

Focus Group Questions

1. Thinking about your elementary science methods course, can you identify any specific class activities that were particularly influential on your ability to teach your science?
    a. *Follow up on what was influential about them.*
    b. *Could be positive or negative.*
2. Do you feel like you were adequately prepared to teach science content?
    a. Why or why not?
    b. What factors do you attribute to that?
    c. *Could be related to this course or science content taught outside of the Edu department.*
3. Focusing on your stage 3 field experience related to science, how do you think what you have learned will affect your classroom practice?
4. Which activities/placements in the field experience for teaching science did you find most useful?
5. Which activities/placements in the field experience for teaching science did you find least useful?
6. Do you have any additional comments or thoughts regarding the methods course or field experiences for teaching elementary science?

Appendix C

Fall 2017 Voluntary Questions

1. How much prior exposure did you have interacting with populations like the ones at Goode? (Low SES, high poverty, ELL)
2. How much of that prior exposure was working in a school setting?
3. What were your feelings about working at Goode at the beginning of the semester? (positive, negative, indifferent)
4. How have your feelings about working with urban populations changed throughout the semester?
5. What did you learn about urban populations by working with Goode students?

Appendix D

Spring 2019 Final Reflections

In this general assignment for all students enrolled in the class, students were asked to reflect on their experiences at their field placement. The prompt is included below. Students were not explicitly asked to discuss their work with students in urban settings, but some chose to do so. I curated some of their responses to include in the qualitative data.

Description

You will observe several science and non-science lessons taught by your cooperating teacher(s) throughout your semester. At the end of the semester, you will write a 1-2 page reflection (double-spaced) of what you observed. Some questions to consider:

- In what ways did the teacher incorporate science? How often?
- What did the teacher do well?
- What would you have done differently?
- What did you have questions about?
- Did the students understand the material? How do you know?
- How did the teacher exemplify (or not) what has been learned in this course?
- Which best practices did the teacher implement?
- How did the teacher implement Next Generation Science Standards?

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Preservice Teachers' Science Process Skills and Science Teaching Efficacy Beliefs in an Inquiry-Oriented Laboratory Context

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ABSTRACT

This study investigated (i) the effect of inquiry-oriented laboratory activities on preservice primary school teachers' (PPSTs) achievement in science process skills (SPS) and science teaching efficacy beliefs, and (ii) changes in groups' reflections of SPS in the laboratory reports as they engaged in the activities. There were 71 PPSTs enrolled in a science laboratory course. Of the 71 PPSTs, 61 who completed the Science Process Skills Test and Teachers' Sense of Efficacy Scale both at the beginning and at the end of the course constituted the sample for the former purpose of the study. On the other hand, 71 PPSTs formed groups to work on the laboratory activities and reports collaboratively, which resulted in a total of 17 groups that were involved in the study for the latter purpose. Findings indicated that PPSTs' achievement in SPS and reflections of SPS in the reports improved in the inquiry-oriented laboratory environment. Furthermore, experiencing the intervention contributed to PPSTs' science teaching efficacy beliefs for instructional strategies, student engagement, and classroom management. Implications for teacher education programs and recommendations for future research are presented.

Keywords: inquiry-oriented laboratory instruction, science process skills, teacher efficacy, science teaching, preservice teachers

Introduction

Science process skills (SPS) are a set of skills that reflect scientists' behaviors when doing science (Padilla, 1990). They are commonly divided into two as basic and integrated. Basic SPS, such as observing, measuring, inferring, classifying, communicating, and predicting, form a basis for learning integrated SPS, which are more complex, such as controlling variables, defining operationally, formulating hypotheses, interpreting data, experimenting, and formulating models (Padilla, 1990). Improving students' SPS has been a major goal of science education due to these skills' vital role in students' science learning (Harlen, 1999). At this point, inquiry-oriented science instruction seems to be a substantial way of developing students' SPS (e.g., Akben, 2015; Koksal & Berberoglu, 2014) because inquiry enables learners to engage in scientific investigation (Bybee, 2006).

Although inquiry has long been encouraged to be used in science classes, there are still deficiencies in teachers' use of inquiry-based activities. One problem in implementation of inquiry-based teaching is regarding teachers' perceptions of laboratory activities; teachers should not only aim to promote students' acquisition of science concepts but also improve students' SPS through these inquiry-based laboratory activities (Akben, 2015). Teacher education programs promoting preservice teachers' practicing inquiry-based activities may help them improve approaches to inquiry activities and ensure proper use of inquiry activities in their own classrooms (Bhattacharyya et al., 2009). Previous research also documented preservice teachers' shortcomings in their own SPS (e.g., Maral et al., 2010; Mbewe et al., 2010). It can be speculated that in order to provide their future students with inquiry-oriented activities, preservice teachers need to experience inquiry-oriented activities during their teacher education programs and develop their own SPS. Considering these, the first purpose of this study was to explore how inquiry-oriented laboratory instruction influences preservice primary school teachers' (PPSTs) achievement in SPS and reflections of SPS in the laboratory reports.

To achieve a desired level of science teaching, in addition to content knowledge and pedagogy, teacher training needs to focus on teachers' efficacy beliefs (Bhattacharyya et al., 2009). Teacher efficacy is teachers' judgments about their abilities to accomplish teaching related tasks (Tschannen-Moran et al., 1998). Indeed, "beliefs are far more influential than knowledge in determining how individuals organize and define tasks and problems and are stronger predictors of behavior" (Pajares, 1992, p. 311). Thus, what teacher education programs should do to foster preservice teachers' science teaching efficacy beliefs should be illuminated (Morrell & Carroll, 2003).

Several studies focused on the effect of inquiry-based instruction on teacher efficacy beliefs within the context of various courses in preservice teacher education programs other than science laboratory course (e.g., Liang & Richardson, 2009; Menon, 2020; Menon & Sadler, 2016; Palmer, 2006; Soprano & Yang, 2013), but few studies examined its effect in laboratory course (Kıran, 2022; Özdilek & Bulunuz, 2009; Şen & Sezen Vekli, 2016). Therefore, there is a need to investigate how inquiry-based laboratory instruction influences preservice teachers' science teaching efficacy beliefs. We propose that not being familiar with the requirements of inquiry-oriented laboratory environment PPSTs may struggle initially. However, as the treatment progresses they may display successful performance in inquiry-oriented laboratory activities which, in turn, may contribute to their appraisals of science teaching abilities. Thus, the second purpose of this study was to investigate the effect of inquiry-oriented laboratory instruction on PPSTs' science teaching efficacy beliefs for instructional strategies, student engagement, and classroom management.

Inquiry-Oriented Science Instruction and its Relation with SPS

Inquiry-oriented science is a major part of educational reform (Alake-Tuenter et al., 2012). According to National Science Education Standards, even students in grades K-4 can ask questions, do simple investigations, use tools to gather data, construct explanations based on the data, and communicate their investigations and explanations. Thus, these students should be given an opportunity to experience active construction of ideas and doing science through inquiry (National Research Council, 1996).

Depending on the information provided to students, there are four levels of inquiry instruction that range from being more teacher directed to more student centered: confirmation, structured inquiry, guided inquiry, and open inquiry (Rezba et al., 1999, as cited in Bell et al., 2005). In confirmation, students are provided with a question, procedure (methods), and expected outcomes (solution), such as verification of a concept in the laboratory after the concept has been taught. In structured inquiry, students engage in a prescribed procedure to answer a teacher posed question. In guided inquiry, the teacher still poses a question but the procedure to be followed for the investigation is determined by students. On the other hand, in open inquiry, students formulate their questions and choose their methods for the investigation. According to students' readiness level, the teacher utilizes the appropriate level of inquiry instruction and as students practice inquiry, they should steadily progress toward higher levels of inquiry (Bell et al., 2005).

Previous research generally indicated that inquiry-oriented science instruction improved students' SPS (e.g., Idul & Caro, 2022; Koksal & Berberoglu, 2014; Mulyeni et al., 2019; Roth &

Roychoudhury, 1993). For example, in a study with second grade elementary school students (Mulyeni et al., 2019), structured and confirmatory inquiry were implemented by using the 5E learning model. Quantitative data analysis revealed that as a result of the implementation process, students' basic SPS of observation, classification, and measurement improved significantly. Qualitative data analysis indicated that hands-on activities, completing worksheets, interaction between students and students, and students and teachers, and observing the teacher and peers while using SPS all contributed to students' development of SPS. In a recent study (Idul & Caro, 2022), the effect of process-oriented guided inquiry learning, in which students work in small groups and collaborate during inquiry, was investigated on high school grade 10 students in a biology class. It was found that process-oriented guided inquiry learning developed students' academic performance in biology, overall SPS, and specifically SPS of observing, classifying, and inferring. There is also evidence for positive effects of inquiry-oriented instruction on preservice teachers' SPS (e.g., Karışan et al., 2016; Yakar & Baykara, 2014). For instance, Karışan et al. (2016) found that PPSTs' SPS increased as a result of reflective inquiry-based science laboratory activities. Another study showed that laboratory activities based on argument-driven inquiry improved preservice science teachers' SPS more than traditional laboratory activities (Demircioglu & Ucar, 2015). However, most of the prior studies measured SPS through achievement tests and calculated total scores and did not give information about specific skills. On the other hand the present study, in addition to exploring SPS as a whole, focused on each of SPS separately. PPSTs' reflections of particular skills were investigated through laboratory reports.

Teaching Efficacy Beliefs and their Relationship with Inquiry-Oriented Science Instruction

Teacher efficacy is teachers' judgments of their capabilities to operate teaching functions (Tschannen-Moran et al., 1998). Teachers' efficacy beliefs influence their goals, enthusiasm, and behavior in the classroom, such as how much effort they exert (Tschannen-Moran et al., 1998). Previous studies showed that teachers' efficacy is closely related to teacher behavior, student behavior, and student achievement (e.g., Ashton & Webb, 1986; Ross, 1992).

In this study, we followed Tschannen-Moran and Woolfolk Hoy's (2001) three dimensional conceptualization which comprises efficacy for instructional strategies, classroom management, and student engagement. Accordingly, efficacy for instructional strategies is related to teachers' beliefs that they can adjust their lesson for the proper level of students, provide alternative explanations when students are confused, and use a variety of assessment strategies. Efficacious teachers for classroom management, on the other hand, believe that they can control disruptive behavior in the classroom and get children to follow classroom rules. Lastly, efficacy for student engagement refers to teachers' beliefs that they can motivate their students and help students value learning. Teachers' efficacy beliefs are context specific, meaning their efficacy is not the same for all school subjects or for all student levels (Tschannen-Moran et al., 1998). In the present study, PPSTs' efficacy specific to teaching primary school science was the focus.

When efficacy beliefs are formed, it is difficult to change them (Tschannen-Moran et al., 1998). Therefore, promoting the efficacy beliefs of preservice teachers is an important role of teacher education programs (Yerdelen et al., 2019). Research provided evidence for the effectiveness of inquiry-based instruction on preservice teachers' teaching efficacy beliefs of science (e.g., Bhattacharyya et al., 2009; Liang & Richardson, 2009). Although most of the previous studies were conducted within the context of a teaching practice course (e.g., Bhattacharyya et al., 2009; Soprano & Yang, 2013), science methods course (e.g., Palmer, 2006; Seung et al., 2019), or science content course (e.g., Liang & Richardson, 2009; Menon & Sadler, 2016), a few studies were carried out in a laboratory course (Kıran, 2022; Özdilek & Bulunuz, 2009; Şen & Sezen Vekli, 2016). For instance, Özdilek and Bulunuz (2009) investigated the effect of inquiry activities in the laboratory course on preservice teachers' science teaching efficacy beliefs. At the beginning of each class, the course instructor explained one of the SPS. Then, prior to hands-on activities, preservice teachers were given detailed information on directions and procedures such as how they would collect and organize data. Findings of the study showed that participants' teaching self-efficacy beliefs improved; however, their levels of efficacy were not at an excellent level. In Şen and Sezen Vekil's (2016) study, the effect of an inquiry approach was investigated in a general biology laboratory-one course with a sample of preservice science teachers. These authors found that at the end of the semester, SPS and laboratory usage self-efficacy beliefs of students in the experimental group instructed with an inquiry-based approach were higher than those of students in the control group instructed with a traditional teaching approach. These studies provide empirical evidence for the support of inquiry-based laboratory activities on preservice teachers' science teaching self-efficacy beliefs and laboratory teaching self-efficacy beliefs. However, the effect of inquiry-oriented laboratory instruction on preservice teachers' science teaching efficacy for instructional strategies, student engagement, and classroom management were not addressed in these studies. In a recent study, Kıran (2022) dealt with this issue, and investigated how preservice science teachers' teaching efficacy beliefs for instructional strategies, student engagement, and classroom management are affected by inquiry-based laboratory activities. The study lasted 14 weeks; three weeks for introducing laboratory rules and organization, three weeks for inquiry instruction and science process skills, and the rest of the weeks included open inquiry laboratory activities. It was found that every dimension of teaching efficacy beliefs of preservice science teachers improved at the end of the semester when compared with the beginning of the semester. We think that providing preservice teachers with a gradual transition for student-centered inquiry activities, namely introducing them firstly with structured inquiry and then with guided inquiry, may be helpful for preservice teachers to get accustomed to this approach. Therefore, there is a need to conduct more studies in order to illuminate the effect of inquiry-oriented instruction employed in the science laboratory course on preservice teachers' science teaching efficacy.

Purpose and Research Questions

This study investigated the influences of inquiry-oriented laboratory instruction. More specifically, it focused on how this intervention affects (i) PPSTs' achievement in SPS and science teaching efficacy beliefs and (ii) groups' reflections of SPS in the laboratory reports. The following research questions (RQs) were addressed:

1. What is the effect of inquiry-oriented laboratory instruction on PPSTs' achievement in SPS?
2. What is the effect of inquiry-oriented laboratory instruction on PPSTs' science teaching efficacy for instructional strategies, student engagement, and classroom management?
3. How do groups' reflections of SPS in the laboratory reports change as they engage in inquiry-oriented laboratory activities?

Method

Design

This study comprised two parts. In the first part, one-group pretest-posttest design was employed to investigate the effect of inquiry-oriented laboratory instruction on PPSTs' achievement in SPS and beliefs of science teaching efficacy (RQ1 and RQ2). The inquiry-oriented laboratory instruction was undertaken within the context of a science laboratory course. The Science Process Skills Test (SPST; Burns et al., 1985) and Teachers' Sense of Efficacy Scale (TSES; Tschannen-Moran & Woolfolk Hoy, 2001) were administered to PPSTs to measure their achievement in SPS and science teaching efficacy beliefs, respectively both at the beginning and at the end of the course. To evaluate the effect of the inquiry-oriented laboratory instruction, PPSTs' pre- and post-treatment scores were compared through paired-samples t-tests. In the second part, qualitative research was utilized to inspect changes in groups' reflections of SPS in the laboratory reports as PPSTs engaged in inquiry-oriented laboratory activities (RQ3). The groups' laboratory reports were analyzed with regard to the groups' reflections of SPS through qualitative data analysis.

Participants

There were 71 PPSTs (46 females, 25 males; 61 sophomores, 10 upper graders) enrolled in a science laboratory course at a public university in the Central Anatolia region of Türkiye[1]. Of the 71 PPSTs, 61 (42 females, 19 males) who completed quantitative data collection instruments both at the beginning and at the end of the course constituted the sample in the first part of the study. On the other hand, 71 PPSTs formed groups of 3-5 members to work on the laboratory activities and reports collaboratively. This resulted in a total of 17 groups that were involved in the second part of the study.

The Context of the Study: A Science Laboratory Course

The science laboratory course was a must course offered in the third semester of primary teacher education programs. The course lasted for 13 weeks, had two sections both taught by the first author, and each section met weekly for a two-hour block.

The course began with instruction of issues including safety in the laboratory, laboratory equipment and materials, and SPS. Then, it proceeded with six laboratory activities related to various science topics: The first activity was a preparatory activity, and the following five activities were inquiry-based activities. PPSTs were informed about the focus of the week beforehand, and in general at the start of each class, a quiz was given with the aim of ensuring PPSTs' preparation for the class. PPSTs worked in groups on the laboratory activities and associated reports. That is, PPSTs worked in groups and designed and/or performed the activities, collected data, and completed the reports through answering the questions with regard to the activities and reflecting on the SPS employed during the activities. The laboratory report sheet was provided to groups at the beginning of each activity and was required to be returned at the end of the class. The instructor monitored groups' work, guided them to do inquiries, evaluated the laboratory reports, and gave feedback to the groups about their comprehension and performance regarding the activities and their use and reflections of SPS.

The Laboratory Activities and Associated Reports

The science laboratory course comprised six laboratory activities. The laboratory activities and associated reports were prepared by utilizing related textbooks (e.g., Arslan et al., 2015) and/or previous research (e.g., Ozdem et al., 2013). The first activity was a preparatory activity to accustom PPSTs to performing an activity and completing an associated report in groups, experiencing certain SPS, and reflecting the skills in the report. More specifically, the activity was related to using a light microscope. Initially, a mini instruction was given to PPSTs about parts, magnification, and usage of a light microscope. Then, they were asked to find images of specimens using prepared slides and

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[1] This study did not cause any physical or psychological harm to the participants. The participants were informed about the purpose of the study and were told that they could withdraw from the study on any occasion. The participants' names were not used in the study; a number was given to each data collection instrument to ensure anonymity.

answer the questions in the given laboratory report (e.g., "Draw the images of the object you are examining when the objectives of 4x and 40x are used and write down your observations"). On the other hand, the subsequent five activities were inquiry-based, and these five activities were the focus of the present study. Activities one through five hereafter refer to inquiry-based activities. Activities one and two were in line with structured inquiry in which PPSTs were provided with an implied research question and a procedure. For example, in activity one, PPSTs were asked to detect characteristics of a letter's (e.g., "R") image on a light microscope. PPSTs were also directed through the procedure with questions given in the related laboratory report (e.g., "How was the image of the letter you examined on the light microscope compared to the letter on the stage?", "Write your observations about the image when the slide was moved to the left, right, backward, and forward"). Activities three through five were congruent with guided inquiry in which PPSTs designed the procedure to be followed to answer the research question given/implied by the instructor. For example, in activity four, PPSTs were asked to design and perform an experiment to explain the relationship between the force exerted on a spring and the extension of the spring. The reason for preferring this sequence was that the course was the first course on science laboratory that PPSTs had taken, and they were not accustomed with inquiry-oriented instruction. Also, during the activities, PPSTs were encouraged to employ a range of SPS and reflect the skills in the reports. Table 1 informs about the laboratory activities and associated reports along with targeted SPS.

Table 1

The Inquiry-Based Laboratory Activities and Associated Reports Along with Targeted SPS

Laboratory activities	**Targeted SPS**		**Descriptions of laboratory activities and reports**
1. Examination of a letter's image through a light microscope	Predicting Observing Recording data	Communicating Interpreting data	PPSTs detected characteristics of a letter's (e.g., "R") image on a light microscope.
2. Inspection of samples through a stereo microscope	Predicting Observing Recording data	Communicating Interpreting data Classifying	PPSTs detected characteristics of an image on a stereo microscope by inspecting samples including a piece of paper with inscription, sand, sugar, salt, and an insect and identified the ways (using top or bottom lighting) to have a clear image.
3. Examination of a plant cell and an animal cell through a light microscope	Predicting Observing Recording data	Communicating Interpreting data Classifying	PPSTs found the images of an onion peel cell and a human cheek epithelial cell and detected the difference in shape between the two cells.
4. Relation between the force exerted to a spring and the extension of the spring	Observing Measuring Formulating a hypothesis Identifying and controlling variables Defining operationally Designing and conducting an experiment	Recoding data Communicating Constructing a table of data Constructing a graph Interpreting data	PPSTs explored the relationship between the force exerted to a spring and the extension of the spring.
5. Density	Observing Measuring Identifying and controlling variables Designing and conducting an experiment Recording data	Communicating Constructing a table of data Constructing a graph Interpreting data	PPSTs explored the relationship between the amount of water and its density and identified the density of an irregularly shaped solid.

Measures

Science Process Skills Test (SPST)

The SPST was developed by Burns et al. (1985) to measure middle and high school students' achievement in integrated SPS. It is a 36-item multiple-choice test with items referring to SPS of identifying variables, operationally defining, stating hypotheses, graphing and interpreting data, and designing investigations. Burns et al. (1985) found the coefficient alpha for the test as .86. The SPST was translated and adapted into Turkish by Geban et al. (1992) who reported the reliability coefficient as .81. Considering Burns et al.'s (1985) view that besides measuring secondary students' SPS achievement, the SPST may be convenient for use in teacher education programs. Considering research that drew on the SPST with data collected from preservice teachers (e.g., Bozkurt, 2014), this study employed the SPST to measure PPSTs' SPS achievement. In this study, pre-treatment and post-treatment test scores yielded satisfactory internal consistency coefficients computed by Kuder-Richardson 20, which were .60 and .83, respectively.

Teachers' Sense of Efficacy Scale (TSES)

The TSES was developed by Tschannen-Moran and Woolfolk Hoy (2001) for gauging teacher efficacy. There are two forms of the scale: a 12-item short form and a 24-item long form. The scale includes three subscales: efficacy for instructional strategies, efficacy for student engagement, and efficacy for classroom management with each subscale having four items in the short form and eight items in the long form. Sample items of efficacy for instructional strategies, student engagement, and classroom management are as follows respectively: "To what extent can you use a variety of assessment strategies?", "How much can you do to get students to believe they can do well in schoolwork?", and "How much can you do to control disruptive behavior in the classroom?". The items are scored on a nine-point scale (1= nothing, 3= very little, 5= some influence, 7= quite a bit, and 9= a great deal).

The long form of the TSES was adapted into Turkish by Çapa et al. (2005) who revealed the reliability and validity of scores acquired from Turkish preservice teachers. Then, Yerdelen (2013) provided reliability and validity evidence for the short form of the scale with Turkish inservice science teachers. Considering that the short form is more advantageous in terms of usability, and it is not more disadvantageous in terms of reliability and validity, the short form was employed in this study. Although the TSES was developed for gauging general teacher efficacy, there are also studies that utilized the TSES to measure science teaching efficacy beliefs (e.g., Kıran, 2022; Yerdelen, 2013). Similar to these studies, and in the current study, the wording of the items in the scale was modified to explore science teaching efficacy. For instance, the item, "To what extent can you use a variety of assessment strategies?", was modified as "To what extent can you use a variety of assessment strategies in science courses?". In the present study, the scale yielded satisfactory reliability with Cronbach's alpha values ranging from .72 to .85 (pre-treatment) and ranging from .66 to .82 (post-treatment).

Laboratory Reports

The five laboratory reports associated with the previously mentioned, inquiry-oriented laboratory activities were utilized to assess changes in groups' reflections of SPS as they engaged in the activities. In addition to guiding PPSTs to complete the activities through inquiry, the questions in the reports directed PPSTs to employ certain SPS and reflect the skills in the reports. More specifically, there were questions associated with particular SPS that required PPSTs to perform the skills (for detailed information see data analysis). Also, each report was comprised of a question which asked PPSTs to elucidate SPS that they employed throughout the activity.

Data Analysis

Data analysis included two parts. In the first part, PPSTs' pre- and post-treatment SPST scores were compared through a paired-samples t-test. To create pre- and post-treatment SPST scores, correct responses given to the items on the SPST were coded with a one, while incorrect responses and responses left blank were coded as zero. Then, scores given to each item on the SPST were summed. Besides, PPSTs' pre- and post-treatment scores for subscales of teaching efficacy beliefs were compared through paired-samples t-tests. Pre- and post-treatment subscale scores were computed by averaging scores given to the items belonging to each subscale.

In the second part, responses in the laboratory reports to the question which asked to elucidate SPS that PPSTs employed throughout the activity and/or to the question associated with the particular skill were evaluated. While accurate responses were scored as one, inaccurate responses and responses left blank were scored as zero. For a response to be considered as accurate, PPSTs were expected to state the name of the skill that they experienced during the activity and provide its explanation by relating the skill with the activity. For formulating a hypothesis, identifying and controlling variables, defining operationally, designing and conducting an experiment, constructing a table of data, and constructing a graph, in addition to the aforementioned criteria, PPSTs' responses to the question related to the particular skill were checked for accuracy. More specifically, to get a score of one for "formulating a hypothesis", groups should provide the name of the skill along with its explanation in relation to the activity and construct a testable hypothesis. For example, Group 13 properly stated and elucidated the skill they experienced during activity four as "Formulating a hypothesis: The potential solution we offered for the experiment" and formulated the hypothesis "As the force exerted to the spring increases, the amount of the spring extension increases". In comparison, Group five responded as "We formulated the hypothesis that different masses affect the length of the spring differently" which was considered as inaccurate because the group did not correctly state the independent variable and did not explicitly specify how the independent variable affected the dependent variable. Table 2 demonstrates sample quotes of groups' responses which were considered as inaccurate and accurate for each of SPS.

While analyzing reports, initially the first author assigned scores. Then, the first and second author went over the responses and scores and discussed the ambiguous parts. Consequently, this resulted in agreed scores along with associated responses.

Table 2

Sample Quotes of Groups' Inaccurate (Score = 0) and Accurate (Score = 1) Responses for Each of SPS

SPS	Score	Sample quote
Predicting	0	"Predicting" (G8-A1) [The group did not provide an explanation of the skill in relation to the activity]
	1	"Predicting: We predicted about how onion peel and epithelial cells would look like" (G6-A3) [The group made predictions about the images of both cells in response to the related question]
Observing	0	"Since we observed objects in terms of shape and color, we made a quantitative observation." (G15-A3) [The group inappropriately labeled the observation as quantitative]
	1	"Observing: We observed the shape and color of the substances we examined. A qualitative observation was made" (G13-A2)
Recording data	0	"Recording data: We prepared a laboratory report." (G1-A4) [The group did not provide an adequate explanation of the skill in relation to the activity]
	1	"Recording data: We recorded the amount of the spring's extension" (G16-A4)
Communicating	0	[All of the groups that got the score of 0 did not identify "communicating" as a response to the related question]
	1	"Communicating: We discussed how to prepare a microscope slide as a group" (G3-A1)
Interpreting Data	0	"Interpreting data: As group members, we compared and interpreted the data each of us obtained" (G16-A3) [The group did not provide an adequate explanation of the skill in relation to the activity. More specifically, the group did not mention about the conclusion group members drew]
	1	"Interpreting data: We interpreted the data we obtained. Drawing a conclusion: We drew a conclusion in line with the data we obtained and the hypothesis we tested: The amount of substance does not affect the density." (G11-A5) [Since interpreting data comprises arranging data and forming conclusions from the arranged data (Padilla, 1990), the group's response was accepted as accurate]
Classifying	0	"Classifying: We analyzed transparent, translucent, and opaque materials by classifying them." (G12-A2). [The group did not classify the materials; the mentioned classification already existed in the related question. The question was that "Considering that the sand is opaque; salt and sugar are translucent; and the insect wing is transparent, discuss with your group friends what kind of lighting is used for each of them".]
	1	[None of the groups provided an accurate response]
Measuring	0	"Measuring: We measured the density of stone and water" (G7-A5) [The density was not measured; it was calculated by using a formula]
	1	"Measuring: We found the masses of the materials (stone, graduated cylinder, graduated cylinder filled with water) to be used in the experiment using a balance. Using graduated cylinder, volumes of water and volumes of 'water + stone' were found" (G14-A5)
Designing and conducting an experiment	0	"Conducting an experiment" (G10-A5) [The group reported only the name of the skill; did not provide an explanation of the skill in relation to the activity]
	1	"Designing and conducting an experiment: We designed the experiment according to the hypothesis we formed and carried out the experiment." (G1-A4) [In response to the related question in the report, the group provided an appropriate design to examine the relation between the force exerted to a spring and extension of the spring]
Identifying and controlling variables	0	"Identifying and controlling variables: We identified and controlled variables throughout the experiment." (G1-A5) [In response to the related question in the report, the group gave an incorrect response by identifying dependent variable as volume and mass of liquid]
	1	"Identifying and controlling variables: We identified dependent and independent variables. We kept other variables constant so that another variable other than the independent variable we specified did not affect the result (controlling)" (G17-A4) [In response to the related question in the report sheet, the group identified the independent variable as the force exerted to a spring (weight), the dependent variable as amount of extension of the spring, and controlled variables as tripod base, metal rods, fixing apparatus, kind of wire, thickness of wire, and length of wire.]

Table 2 *Continued*

SPS	Score	Sample quote
Constructing a table of data	0	[All of the groups that got the score of 0 did not specify "constructing a table of data" as a response to the related question]
	1	"Constructing a table: We constructed a mass-density table." (G3-A5) [The group provided an appropriate mass-density table in response to the related question]
Constructing a graph	0	"We constructed our graph according to the results of the experiment." (G4-A5) [Although independent and dependent variables were mass of water and density of water respectively, the group constructed a volume-density graph, which is not exactly congruent with variables of the activity]
	1	"Constructing a graph: We constructed a mass-density graph." (G3-A5) [The group provided an appropriate mass-density graph in response to the related question]
Formulating a hypothesis	0	"We formulated the hypothesis that different masses affect the length of the spring differently" (G5-A4) [The group did not correctly state the independent variable and did not explicitly specify how the independent variable affected the dependent variable]
	1	"Formulating a hypothesis: The potential solution we offered for the experiment." (G13-A4) [In response to the related question in the report, the group formulated an appropriate hypothesis which was that "As the force exerted to the spring increases, the amount of the spring extension increases".]
Defining operationally	0	"Defining operationally: We made the operational definition of the variables." (G10-A4) [The group's operational definition of the dependent variable was that "variable that changes depending on the independent variable", which is not appropriate because it did not include information about how the variable was measured]
	1	"Defining operationally: We identified the variables and defined how to measure and observe the variables." (G17-A4) [The group operationally defined the dependent variable, that is extension of the spring, as "measuring the change in the length of the spring depending on the independent variable through a ruler"]

Note. 'G' and 'A' refer to group and activity, respectively.

Results

Effect of the Intervention on PPSTs' Achievement in SPS

PPSTs' scores on the SPST were utilized as indicators of their achievement in SPS. Participants' average pre-treatment SPST score was found as 19.84 out of 36, demonstrating a moderate level of achievement in SPS. On the other hand, the average SPST score increased to 27.74 on the post-treatment test, suggesting a high level of achievement. To investigate whether there was a significant change in PPSTs' average SPST score after inquiry-oriented laboratory instruction, a paired-samples t-test was conducted. The paired-samples t-test resulted in a statistically significant increase in PPSTs' achievement in SPS following the treatment, and an eta square (η^2) value demonstrated a large effect size (Cohen, 1988). See Table 3 for this information.

Table 3

Descriptive Statistics for SPST Scores and Paired-Samples t-test Results

	Pretest		**Posttest**		**Gain score (posttest-pretest)**	**SE**	**t**	**df**	**p**	**η^2**
	M	**SD**	**M**	**SD**						
SPST	19.84	3.96	27.74	5.23	7.90	0.65	12.23	60	0.00	0.71

Effect of the Intervention on PPSTs' Science Teaching Efficacy Beliefs

PPSTs' scores on the subscales of the TSES were considered as indicators of their science teaching efficacy for instructional strategies, student engagement, and classroom management. Participants attained average pre-treatment scores of 5.80 for efficacy on instructional strategies, 5.75 for efficacy on student engagement, and 6.21 for efficacy on classroom management on a nine-point scale. These average scores suggested a moderate sense of efficacy beliefs. After the treatment, the average scores increased to 6.30 for efficacy on instructional strategies, 6.46 for efficacy on student engagement, and 6.76 for efficacy on classroom management. To evaluate changes in PPSTs' science teaching efficacy beliefs components, three paired-samples t-tests were carried out. Bonferroni adjustment with the reduced alpha level of .017 (.05/3) was applied to decrease the probability of making a type I error. The analysis resulted in a significant increase in all efficacy aspects. An eta square (η^2) value indicated that increase in efficacy for student engagement was large, and medium for instructional strategies and classroom management according to Cohen's (1988) criteria. See Table 4.

Table 4

Descriptive Statistics for Scores of Science Teaching Efficacy Beliefs Subscales and Results of Paired-Samples t-tests

	Pretest		**Posttest**		**Gain score (posttest-pretest)**	**SE**	**t**	**df**	**p**	η^2
	M	**SD**	**M**	**SD**						
Instructional strategies	5.80	1.50	6.30	1.29	0.50	0.16	3.15	60	0.00	0.14
Student engagement	5.75	1.31	6.46	0.92	0.71	0.14	4.93	60	0.00	0.29
Classroom management	6.21	1.28	6.76	1.12	0.54	0.13	4.11	60	0.00	0.22

Changes in Groups' Reflections of SPS in the Laboratory Reports

When groups' responses for each of SPS over the laboratory reports were examined, it was seen that the influence of the intervention on PPSTs' reflections of SPS was not uniform. See Table 5.

Table 5

Total Number of Groups That Provided Accurate Responses for Targeted SPS in the Laboratory Reports

Laboratory Reports	**Communicating**	**Predicting**	**Designing and conducting an experiment**	**Constructing a table of data**	**Recording data**	**Interpreting data**	**Measuring**
1	7	7	-	-	6	5	-
2	13	15	-	-	5	8	-
3	13	15	-	-	11	9	-
4	14	-	13	11	10	6	11
5	15	-	14	14	14	10	11

Note. "-" indicates that the skill was not addressed in the report.

Table 5 *Continued*

Laboratory Reports	Observing	Constructing a graph	Defining operationally	Formulating a hypothesis	Identifying and controlling variables	Classifying
1	10	-	-	-	-	-
2	17	-	-	-	-	0
3	14	-	-	-	-	0
4	12	12	8	13	10	-
5	10	10	-	-	4	-

Note. "-" indicates that the skill was not addressed in the report.

More specifically, as PPSTs engaged in the laboratory activities, the number of successful groups mostly increased, and to a lesser extent decreased, or remained the same. For SPS of communicating, predicting, designing and conducting an experiment, and constructing a table of data, the number of groups that were accomplished in the last report, in which the skill was included, was greater than that in the first report in which the skill was addressed. For these skills, as the treatment progressed, the number of accomplished groups increased or remained the same. For example, the skill of predicting was targeted in laboratory reports one, two, and three. Seven of the 17 groups gave an accurate response for this skill in laboratory report one. Of these seven groups, five continued their success in all of the subsequent laboratory reports and the rest of the groups (*n*=2) succeeded in one of the two subsequent reports. The groups that did not answer accurately in laboratory report one (*n*=10) showed an attainment in laboratory report two and/or laboratory report three. As a result, the total number of groups that gave an accurate response was 15 in each of laboratory reports two and three. For recording data and interpreting data, although the number of successful groups fluctuated over the reports, it was greater in the last report than that in the first report. For measuring and observing, the number of achieved groups in the last report was equal to that in the first report in which the skill was addressed. For observing, initially an increase and then a continuous decrease was detected in the successful groups. However, both skills were accurately reflected in the reports by most of the groups.

Constructing a graph skill was targeted in two of the activities. Although the number of groups that achieved decreased slightly from the first report, in which the skill was targeted to the last report, in both reports more than half of the groups were accomplished. The skills of defining operationally and formulating a hypothesis were addressed in only one activity and slightly less than half and most of the groups respectively accomplished these skills.

On the other hand, the skill of identifying and controlling variables was targeted in two of the activities and although more than half of the groups succeeded in the first report, in which the skill was targeted, a noticeable decrease was observed from the first to the last report. More specifically, 10 of the 17 groups gave an accurate response for this skill in laboratory report four. Among the mentioned 10 groups, three groups maintained their accomplishment in laboratory report five, but other groups (*n*=7) did not. Of the seven groups that did not respond accurately in laboratory report four, one revealed an achievement in laboratory report five. Totally, only four groups responded accurately in laboratory report five. Additionally, two of the activities addressed classifying skill but none of the groups showed accomplishment.

Discussion

This study assessed how inquiry-oriented laboratory activities affect PPSTs' achievement in SPS and science teaching efficacy beliefs and inspected groups' reflections of SPS in the laboratory reports. Findings showed that PPSTs' achievement in SPS increased substantially following the intervention. When groups' reports were examined, it can be concluded that the intervention was effective -albeit to varying degrees- to improve PPSTs' reflections of most of the targeted SPS. We think that as PPSTs experienced the activities, they had the opportunity to use SPS, hold discussions about the skills within their groups, and reflect on the skills they used during the activities in the reports, all of which supported their comprehension, use, and reflections of SPS. Findings of previous studies also indicated positive influences of inquiry-based instruction on preservice teachers' SPS (e.g., Demircioglu & Ucar, 2015; Karışan et al., 2016), however, the present study extended our understanding by providing evidence about changes in particular SPS through evaluation of laboratory reports.

Although PPSTs' reflections of most of the targeted SPS was promising, this was not the case for two of the skills. For the skill of identifying and controlling variables, a considerable decrease in the number of achieved groups was detected from the first report, in which the skill was targeted, to the last report and none of the groups succeeded at the skill of classifying in the reports. Accordingly, it can be inferred that the activities of inspecting samples through a stereo microscope and examining the cells through a light microscope were insufficient for supporting PPSTs' reflections of classifying skill. In a similar vein, the activity about density was inadequate for underpinning PPSTs' reflections of identifying and controlling variables skill. Hence, the aforementioned activities should be improved to promote PPSTs' reflections of the skills of classifying and identifying and controlling variables. We suggest that selection of activities to be used in the science laboratory is important and more activities which address the skills of classifying and identifying and controlling variables can be incorporated to overcome deficiencies at these skills. Mastery of SPS is essential for science teaching and in order to get expertise, preservice teachers should develop a sound understanding of SPS, and practice these skills, in the guidance of university programs (Ango, 2002).

This study also revealed that being exposed to the intervention, PPSTs felt more efficacious about instructional strategies, student engagement, and classroom management. Gaining experiences in an inquiry-oriented laboratory context contributed to PPSTs' efficacy beliefs about how to provide explanations to students who are confused about science concepts, evaluate students' science learning, engage students with a science course, motivate students to learn science, and manage class in the science course. As the treatment progressed, PPSTs showed generally more successful performance in the activities as evidenced in the reports and their SPSs improved which, in turn, might raise their appraisals of science teaching abilities. Previous research findings also suggested that inquiry promoted the development of preservice teachers' efficacy beliefs (e.g., Liang & Richardson, 2009; McCall, 2017; Palmer, 2006; Seung et al., 2019; Soprano & Yang, 2013) and cultivating mastery experiences fosters self-efficacy (Zientek et al., 2019). However, most of the prior studies were conducted within the context of teaching practice, science methods, or science content courses, while the present study supported its positive effects within the context of a science laboratory course. As mentioned before, a few studies (i.e., Özdilek & Bulunuz, 2009; Şen & Sezen Vekli, 2016) examined the effect of inquiry-based laboratory instruction on preservice teachers' science teaching and laboratory teaching self-efficacy beliefs and demonstrated positive effects. To our knowledge, one study (Kıran, 2022) investigated the effect of open inquiry-based laboratory activities on preservice teachers' efficacy beliefs for instructional strategies, student engagement, and classroom management. It was found that at the end of the semester preservice teachers' efficacy beliefs improved in all three dimensions. Findings of the current study support Kıran's (2022) findings and extend these findings such that positive effects were also attained with structured and guided inquiry activities. Science laboratory has an important role in science education, such as the development of students' understanding of science concepts and how science works (Hofstein & Mamlok-Naaman, 2007). In an inquiry-oriented laboratory course, preservice teachers have opportunity both to study subject matter and practice inquiry (Kıran, 2022) and incorporating both content and method has the potential to improve teaching efficacy beliefs of preservice teachers (Deehan et al., 2019). Thus, we think that PPSTs' gaining experience in an inquiry-oriented laboratory environment and improving their science teaching efficacy beliefs within this context are important for their future teaching practices.

Based on the findings of the present study, we suggest that in teacher education programs, PPSTs can be provided with opportunities to experience inquiry-oriented instruction and a science laboratory course seems to be very appropriate for this purpose. Laboratory activities designed and performed in accordance with inquiry-based instruction appeared to support PPSTs' achievement in and reflections of SPS and beliefs of science teaching efficacy. Therefore, it is worthwhile for teacher education programs to employ an inquiry approach in training prospective teachers.

Limitations of the Study and Recommendations for Future Research

This study has some limitations that need to be clarified and some recommendations for future research. First, findings of this study demonstrated increases in PPSTs' achievement in SPS and science teaching efficacy beliefs after attending the intervention. However, this does not mean that the intervention caused these increases; other factors that have affected the results may exist (see Fraenkel et al., 2012). Future studies can include a comparison group to argue for causality more strongly. Second, further studies can include individual interviews with PPSTs to attain in-depth information about their understanding of SPS. Third, the present research was limited to five laboratory activities designed and implemented in compliance with structured inquiry and guided inquiry. We recommend future research to include inquiry-oriented activities enabling preservice teachers to experience open inquiry as well. Fourth, there were 13 total SPS addressed in the activities and their presence varied. Since formulating a hypothesis and defining operationally were addressed in only one activity, it is not possible to investigate changes in groups' reflections of these skills in the reports. In addition to this, a small number of activities may not be adequate for promoting PPSTs' comprehension of the targeted skill and for assessing groups' reflections of the skill. In future studies, the targeted skills can be addressed in more activities.

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