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CHAPTER 4

EDUCATING EFFECTIVE SCIENCE TEACHERS

Preparing and Following Teachers Into the Field

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Linking Teacher Preparation Program Design and Implementation to Outcomes for Teachers and Students, pages 87–129

The landscape of teacher preparation is complex and from a research perspective presents itself as a multilevel, multivariable puzzle. For decades, federal and state policymakers, teacher education institutions, educational researchers, school districts, administrators, and other stakeholders have tried to determine and measure the key, malleable factors that result in effective teaching. In a still-referenced vision of teacher preparation, Bransford, Darling-Hammond, and LePage (2007) highlighted three areas of skills, knowledge, and dispositions important for teaching effectiveness:

> (a) knowledge of learners and how they learn and develop within social contexts; (b) conceptions of curriculum content and goals: an understanding of the subject matter and skills to be taught in light of the social purpose of education; and (c) an understanding of teaching given the content and learners to be taught, as informed by assessment and supported by classroom environments. (p. 10)

In the United States, due to a lack of standardization, a large variety of approaches to teacher education have been developed and are overseen by a similarly wide range of state certification policies that affect over 2,100 teacher preparation programs (TPPs; National Commission on Teaching and America's Future, 2016). Through all the research that has been conducted on teacher preparation, no one factor can independently account for observed variability in teacher effectiveness; however, rarely has research been conducted systematically to better inform optimal TPP designs. To address the knowledge gap, Cochran-Smith and Villegas (2016) encourage educational researchers to produce studies that examine "the impact and implications of particular mixes of teacher characteristics, school contexts, and program features" (p. 458). Such studies are especially needed in science education, specifically of TPPs that focus on practicing teaching and learning science using scientific practices (i.e., collecting and analyzing data, carrying out investigations), collaborative work, or a project-based approach to understand science content (van Driel, Berry, & Meirink, 2014; Windschitl & Stroupe, 2017). Due to space constraints we also refer readers to chapters on science teacher preparation (Loughran, 2014) and teacher knowledge (van Driel et al., 2014) for more comprehensive reviews.

The goal of the *Next Generation Science Standards* (NGSS; NGSS Lead States, 2013) is to educate K–12 students to be scientifically literate citizens, as well as encourage more students to pursue science, technology, engineering, and mathematics (STEM) careers to meet the national call for a more highly qualified workforce. This national vision has been outlined in such reports as *Before It's Too Late* (National Commission on Mathematics and Science Teaching for the 21st Century, 2000) in which there was an urgent call for better prepared science and math teachers and systematic professional development to reform K–12 mathematics and science education.

In a review chapter, Bianchini (2012) summarized what researchers have learned about the views, experiences, and classroom practices of beginning science teachers. She found that little was known about the science teaching induction period and recommended that more studies follow beginning science teachers from preservice teacher education into classroom practice, and trace connections, or lack thereof, across induction training, beginning teachers' classroom practices, and student learning. Our research contributes to designing science TPPs to prepare teachers who can provide engaging, reform-based, learning opportunities for diverse students.

This chapter focuses on: (a) our development of a research-based, graduate-level science TPP for teachers with a degree in science; (b) an analysis of teachers' subject matter knowledge (SMK) as it relates to their subsequent use of inquiry-based instruction; and (c) results of a longitudinal study of beginning science teachers who graduated from a master's level TPP in comparison with the instructional practices of science teachers prepared through a traditional undergraduate program. We offer what we consider to be a typical case of an undergraduate and less typical case of a graduate science teacher preparation program that occur at a large, land-grant, 4-year state university in a Great Plains state in the United States. The undergraduate and graduate programs have some overlapping coursework and clinical experiences, but provided different entry points, depth of coursework, culminating degrees, and rates of completion.

CONCEPTUAL FRAMEWORK AND BACKGROUND LITERATURE

Rationale for Study

There are few comprehensive studies of beginning science teachers that correlate aspects of teacher preparation programs with enacted teaching practices (NRC, 2010). Our work begins to address this research gap. The two TPPs in the study focused on developing preservice teachers' inquiry-based science instruction, classroom discourse, knowledge of student diversity, and curriculum development in accordance with reform-based science education standards and practices. We compare the undergraduate program to the graduate program, which is more rigorous in terms of requiring more science and more education coursework. We explore how program factors, including subject matter knowledge and pedagogical knowledge, affected beginning science teachers' instruction. By studying how individual aspects of teacher qualifications and teaching interact, we can better understand how to prepare teacher candidates during the induction period to reduce attrition and accelerate professional growth.

Conceptual Framework

We present our study's conceptual framework in Figure 4.1. The key aspects of the TPPs are grouped by SMK, pedagogical knowledge, and knowledge of learners. We consider SMK to be a mediating variable along with teachers' internal factors that include, but are not limited to, teacher self-efficacy, beliefs, and attitudes. The learning in the TPPs is then mediated by these factors, resulting in more or less reformed-based instruction. We make a distinction between the broader classification of *reform-based teaching* and *inquiry-based instructional practices*, which are a particular set of desired scientific practices that science teachers should strive to include in science lessons. We measured teachers' SMK, self-efficacy, and beliefs about reform-based teaching; in this chapter we report mainly on the relationship between SMK, the effect of having completed an undergraduate or graduate science TPP, and beginning science teachers' implementation of inquiry-based science lessons. We organize our literature review in the same way in the sections that follow.

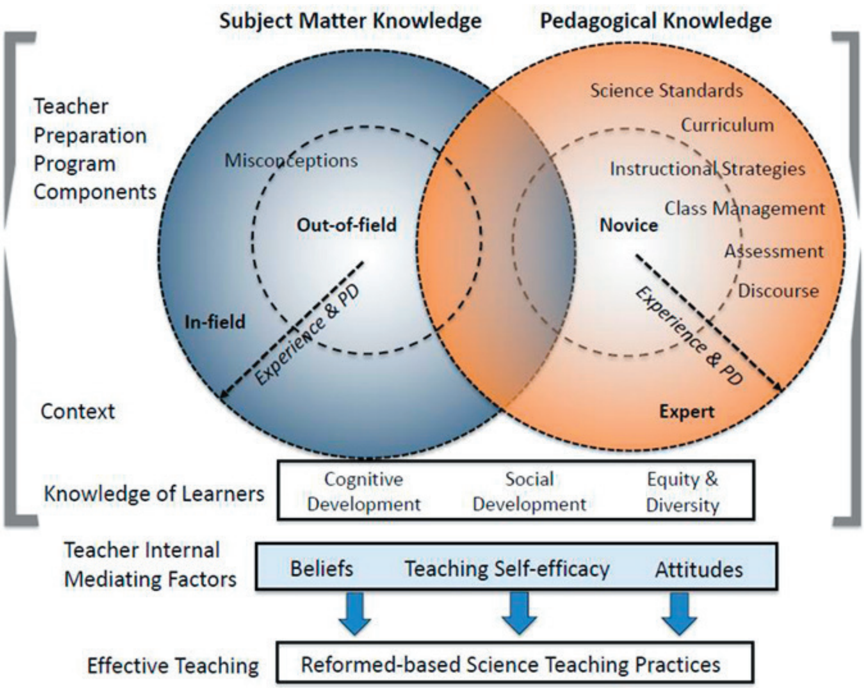


Figure 4.1 Conceptual framework of teacher preparation program and reformed-based science teaching practices.

Teachers' Subject Matter Knowledge and Misconceptions in Science

With insufficient SMK, teachers may have a weak foundation for teaching science (Yip, 1998). Moreover, weak SMK might prevent teachers, especially novice teachers, from using inquiry-based teaching methods (Roehrig & Luft, 2004). This is a critical issue for teachers who are assigned to teach out-of-field in a subject area in which they are not certified (e.g., teaching chemistry when only certified for biology). Strong SMK may help teachers to take more risks in their instructional strategies (Nehm & Ridgeway, 2011; Treagust, 2010) and trust themselves to facilitate students' learning using scientific practices and to elicit students' thinking.

A critical role of science teachers in the development of their students' scientific literacy is to address students' common misconceptions. Insufficient SMK and teachers' failure to understand scientific theories and concepts may result in the spread of misconceptions. Misconceptions are "scientifically incorrect ideas that are persistent and commonly held" (Leonard, Kalinowski, & Andrews, 2014, p. 180). They are considered obstacles to new learning, difficult to change, and persist over time (Hamza & Wickman, 2008). To address students' misconceptions, teachers must identify those misconceptions and create proper remediation that confronts and corrects them (Tekkaya, 2002). While there are few studies about teachers' misconceptions and minimum SMK to teach science, science education researchers agree that misconceptions do reflect insufficient SMK for teaching (Sadler & Sonnert, 2016).

Therefore, TPPs should foster strong conceptual understanding by requiring a set of subject matter courses that strongly align with the teaching competencies that future teachers will be required to teach. Otherwise, teacher educators risk endorsing teachers with subject-specific misconceptions that could be transferred to students through overgeneralizations, inadvertent poor planning and execution of lessons that affects students' long-term learning (Hashweh, 2002; Kikas, 2004; Murphy, 2005; Özmen, 2010). Since teachers play a crucial role in addressing misconceptions, the quality of science teacher preparation could characterize the effectiveness of future science instruction (McDermott, 1990). In summary, these few studies suggest that strong SMK is likely to facilitate science teachers' use of inquiry-based teaching practices and reduce teachers' and students' misconceptions.

Science Teachers' Pedagogical Knowledge and Curricular Choices

Science is considered an indispensable part of K–12 curriculum, especially with the introduction of the *National Science Education Standards* in the mid-1990s (NRC, 1996). Science education supports the development of the next generation of scientists, engineers, and innovators, and is also important for educating informed citizens in a world influenced by technology, scientific values, and ideas (Osborne, 2007). Scientifically literate citizens should be able to:

- understand, use, and interpret scientific explanations of the natural world;
- generate and evaluate scientific evidence and explanations;
- understand the nature and development of scientific knowledge; and
- participate productively in scientific practices and discourse (NRC, 2012, p. 251).

Reform-based science educators strive to construct inquiry-based curricula that promote these principles to develop students' scientific literacy and higher-order thinking skills. Teachers' curricular choices control students' opportunities to learn science. While the depth of science content in lessons varies, it should be sufficiently rigorous to challenge all students.

Teaching science through inquiry-based instruction. Based upon social constructivist theories of learning, the science education community has concluded that *teaching science as inquiry* or inquiry-based instruction is the most effective method for teaching science (Crawford, 2014; Osborne, 2014). In the *Next Generation Science Standards* (NGSS), inquiry is broken into *scientific practices* (e.g., planning and carrying out investigations, analyzing and interpreting data, and arguing from evidence; NGSS Lead States, 2013). Inquiry-based instruction is important for 21st century learning and contributes to developing students' skills such as argumentation, creativity, critical thinking, and decision-making. Unfortunately, the *2012 National Survey of Science and Mathematics Education* (Banilower, Trygstad, & Smith, 2015) revealed low use of inquiry-based practices among science teachers.

Inquiry-aligned assessment practices. Effective teaching starts with planning (Wiggins, 1998) and determining what students already know about a topic by assessing prior knowledge (Bell & Cowie, 2001). Assessment of prior knowledge exposes misconceptions that teachers should address during instruction. Bell and Cowie (2001) identifed teacher noticing and action in response to assessment data as critical elements of formative assessment. Specifically, formative assessment requires teachers to adapt instruction to students' needs based on the evidence collected. Therefore, strong SMK and a rich pedagogical tool box supports adaptive instruction by enabling teachers to find alternative ways to accomplish learning objectives.

Greater teaching experience can yield stronger understanding of how students learn and what is challenging for students to learn. A lack of teaching experience can be balanced with strong SMK and exemplary internship mentoring during the TPP. Therefore, as we certify new teachers, we need to ensure that they have sufficient SMK and pedagogical knowledge to develop high self-efficacy with using assessment during inquiry-based science instruction.

Knowledge of Students: Equity and Diversity Issues

Inquiry-based instruction can also be an instrument of social justice in teaching diverse students; inquiry-based curricula has been shown to support students with special needs as well as English language learners (Lee & Luykx, 2007; McGinnis & Stefanich, 2007). By employing scientific practices within experiential learning-focused curricular activities, teachers can encourage all students to engage in scientific explanations, reasoning, and construction of new knowledge, through understanding of different social meanings and using multiple realities (Calabrese-Barton, 1998; Windschitl, Thompson, Braaten, & Stroupe, 2012). Science teachers should facilitate and model a scientific classroom discourse community in which all perspectives and experiences are valued in the process of scientific meaning making (Lewis, Baker, Bueno Watts, & van der Hoeven Kraft, 2016).

Mediating Factors That Support or Inhibit Reform-Based Science Teaching

Several internal factors have been shown to be mediating factors in either supporting or inhibiting change in teachers' instructional practices. Some of these include self-efficacy, attitudes, and beliefs about reform-based practices in science education that have been included in national standards documents (i.e., NGSS).

Teacher self-efficacy. Teachers' self-efficacy and inquiry-based instruction seem to have a strong relationship. For example, high levels of teacher self-efficacy have long been shown to be an indicator of more innovative teaching (Guskey, 1988) and to be related to higher student achievement (Evans, 2011). Lakshmanan, Heath, Perlmutter, and Elder (2011) found a positive correlation between the amount of growth in self-efficacy and the extent to which inquiry-based instruction was implemented by elementary and middle-school science teachers. Therefore, teachers who have high self-efficacy are more likely to try new teaching strategies, provide opportunities for students to engage in scientific practices, and address students' misconceptions. However, it is important to note that sometimes teachers have conflicting, or competing belief sets (Crawford, 2007), or experience school culture and external pressures (McGinnis, Parker, & Graeber, 2004) that can disrupt the positive relationship between self-efficacy and inquiry-based science instruction. Therefore, it is even more important in such cases that teachers have strong SMK so that they can be sufficiently self-efficacious to be critical of curricular and instructional mandates.

Attitudes and beliefs about science teaching and learning. Problematically, inquiry-based instruction that supports authentic learning is not common in secondary science classrooms. Science teachers often rely on direct instruction, teacher-centered methods, and verification lab activities over inquiry-based instruction (Crawford, 2014). Many new teachers have had little experience with learning through inquiry-based instructional approaches during their own secondary school experiences but were still successful in science

(Windschitl & Stroupe, 2017). Thus, TPPs are challenged to prepare science teachers to think beyond their own experiences to embrace using inquiry-based pedagogical strategies by changing their preconceived attitudes and beliefs about teaching and learning science. While many programs use constructivist strategies and theories in teaching methods courses, these may be insufficient to induce conceptual change in preservice science teachers with strong beliefs about a teacher-centered classroom (Feldman, 2000). An excellent review of science teachers' attitudes and beliefs (Jones & Leagon, 2014) can be found in the most recent volume of the *Handbook of Research on Science Education* (Lederman & Abell, 2014).

Beginning Science Teachers' Instructional Practices

Upon graduation from a TPP, science teachers should have sufficient SMK, pedagogical knowledge, and knowledge of students to implement a wide range of science curriculum (NRC, 2010). As Hill, Rowan, and Ball (2005) indicated, teachers highly proficient in a subject will help others learn that subject "only if they are able to use their own knowledge to perform the tasks they must enact as teachers" (p. 376). That is, science teachers' strong SMK facilitates understanding content and choosing effective strategies to support student learning. TPPs should prepare science teachers to use their SMK to develop inquiry-based instruction to connect students' prior knowledge and everyday experiences with science content.

However, despite completing reform-based TPPs, beginning secondary science teachers often tend to revert to more traditional educational practices during their first years as teachers (Russell & Martin, 2014). For example, beginning teachers often lack the ability to demonstrate the connection between science and everyday life (Bianchini, 2012) or identify big ideas or substantive relationships between scientific concepts to help students to understand natural phenomena (Windschitl et al., 2012). Inquiry-based instruction requires beginning science teachers to reflect on instructional practices, strategies, and routines in order to mature and transform into effective professionals (Duffy, Miller, Parsons, & Meloth, 2009). Reflection and metacognition help novice teachers to plan, monitor, and assess their science teaching experiences, improve inquiry-based teaching practices, and increase their self-efficacy. Moreover, science teachers should learn adaptability, social skills, non-routine problem-solving skills, self-development, and systems thinking (Treagust & Tsui, 2014) to develop, for example, formative assessment strategies. Therefore, both preparation and induction phases should include opportunities for teachers to reflect upon their development as teachers and learn from their experience. Experience should support novice teachers to develop a greater capacity for implementing lesson plans effectively, design better student-centered strategies, enact inquiry-based instruction, and be more responsive to student needs (Bianchini, 2012). Nonetheless, how teachers learn from experience remains poorly understood in science education (Russell & Martin, 2014) and more work should be done to understand the interaction between beginning teachers' knowledge, reflection, practices, and professional growth.

TEACHER PREPARATION PROGRAM STUDY CONTEXT

Our longitudinal study focused on two secondary science teacher programs, one at the undergraduate level and one at the graduate level, at the University of Nebraska-Lincoln (UNL), a large Midwestern, land-grant, 4-year state university. For the graduate-level TPP, we recruited teacher candidates who had earned at least a bachelor's degree in a scientific field, thus meeting a key element of the federal definition of a "highly-qualified" teacher. This Master of Arts in teaching (MAT) program is a 14-month, 42-credit hour program that provides a pathway for recent science graduates and practicing scientists to become science teachers. MAT students begin as a cohort in May and are expected to graduate in August of the following year. Table 4.1 summarizes program coursework and how it differs from the traditional undergraduate program that did not require an undergraduate

TABLE 4.1 Comparison of Undergraduate and MAT Teacher Education Programs

Program	Undergraduate	Master of Arts
Science Coursework	**Prior and concurrent to acceptance:** Sufficient science coursework for Nebraska secondary science teaching endorsement (~24 credit hours on one area with another 12 hours among other three areas).	**Prior to Acceptance:** Undergraduate major in one area of science; some MA students have graduate-level science coursework or advanced degree.
Education Coursework	**Pre-professional education coursework** (including the common coursework with *): Foundations of Education; Adolescent Development & Practicum (13 credit hours)	**MAT coursework:** History and Nature of Science (Cohorts 1–2 only); Reading in the Content Areas (Cohort 3 and onward); Teaching ELLs in the Content Area; Intro to Educational Research; Curriculum Theory; Teacher Action Research Project
Common Coursework	Accommodating Exceptional Learners Adolescent Development* Science Teaching Methods (two classes, each with a practicum experience) Multicultural Education* or Pluralistic Society	
Resulting Degree	BA Secondary Science Education	MA with emphasis in science teaching

degree in science (Lewis, Musson, & Lu, 2014). The MAT program has coursework required for teacher certification, graduate-level courses that include a capstone action research project, and extensive (650 hours or more) clinical experiences.

Student Diversity and Science Achievement

On an annual basis, through both programs, UNL educates 35–40% of Nebraska's newly certified secondary science teachers. Like other largely rural states, Nebraska has many small school districts in small population centers classified as rural (79.5%) and small towns (15.6%) with high levels of local control. Most teachers in our MAT program were supported by National Science Foundation Noyce stipends that required them to teach in a high-need school district for 2 years and most of them took teaching positions in high-need schools.

While Nebraska K–12 teachers are overwhelmingly White, female, and middle class, their students are more ethnically diverse with higher rates of poverty. A recent National Assessment of Educational Progress (NAEP) report (U.S. Department of Education [ED], Institute of Education Sciences [IES], 2015)[1] indicated that 43% of Nebraska youth qualify for free or reduced lunch (FRL), which is similar to the national average; nationwide, about half of all children qualify for FRL. In 2015, on the NAEP science test, Nebraska eighth-grade students performed slightly above average with a score of 160, as compared to the national average score of 153. There were score gaps between White students and Black (–29 points) and Hispanic students (–23 points), as well as a gap between students who qualified for FRL (–21 points) and those who did not (ED, IES, 2015).

Science Content Knowledge

The UNL's TPP candidates can be grouped into three categories: (a) undergraduates seeking a BS degree in secondary science education, (b) recent content-area BS graduates who start the MAT program upon completion of a BS in an area of science, and (c) science professionals who are changing careers to become teachers and enroll in the MAT program. Both undergraduate and graduate programs meet the state's minimum endorsement requirements (Table 4.2).

The undergraduate program results in a major in secondary science education with 24 credit hours in one area of science. In addition to the courses in the chosen main science area, each endorsement area requires

TABLE 4.2 Teaching Qualifications

Nebraska State Secondary Science Teacher Endorsements

- A single-subject endorsement requires 24 credit hours as a minimum in 1 of 4 core science areas (biology, chemistry, physics, or earth and space science)
- Many Nebraska science teachers apply for a "broad field science endorsement," which allows science teachers to teach any area of science, but only requires a minimum of 12[a] credit hours in each of the 4 areas to do so.

NSF/Federal Definition of "Highly qualified" Teacher

- NSF Noyce/Federal guidelines define "highly qualified" science teachers as having an undergraduate major in the content area that they teach. This could be a hybrid of science and education coursework (i.e., a secondary science education major with teaching credential) instead of an undergraduate science degree.

[a] Effective 2012

coursework in supporting sciences. For example, teacher candidates seeking a biology endorsement are also required to take chemistry, Earth and space science, and physics courses, totaling a minimum of 12 credit hours.

Beyond Mandated Teacher Certification Coursework: MAT Program

In response to the need for more highly qualified teachers prepared to teach diverse learners, we designed a rigorous MAT program that recruited individuals with at least an undergraduate degree in science. This 42 credit-hour program could then focus on education coursework and pedagogy, including courses in teaching English language learners and the nature of science. At the third cohort, we replaced the nature of science course with a course in reading in the content areas. MAT teacher candidates were also required to complete a teacher action research project and coursework in curriculum theory and educational research. Conversely, undergraduate teacher candidates only needed to take the minimum coursework required by the state (Table 4.2).

Common Requirements of the Teacher Preparation Programs

In preparing teachers through both programs, we were mindful of the Interstate Teacher Assessment and Support Consortium (InTASC) standards (CCSSO, 2011), as well as the National Council for the Accreditation of Teacher Education (NCATE) standards (NCATE, 2008).[2] We also followed the National Science Teacher Association (NSTA) science teacher preparation standards (Veal & Allen, 2014).

Science Teaching Standards and Teaching Methods Coursework

The UNL's two science teaching methods classes have aligned curriculum development and lesson planning with the national framework for K–12 science education (NRC, 2012) and resulting *Next Generation Science Standards* (NRC, 2013), which Nebraska adapted as its state science standards in September 2017. Both TPP programs were designed to emphasize constructivist teaching principles, such as inquiry and active learning approaches. The MAT program was aligned with the priorities of two National Science Foundation (NSF) Robert Noyce Teacher Scholarship program grants that provided stipends for preservice science teachers with strong content knowledge (i.e., had an undergraduate degree in science). The NSF required teacher candidates with Noyce stipends to complete a 2-year service requirement by teaching in high-need schools following graduation.

Science-specific pedagogy is emphasized in two semester-long teaching methods courses, and preservice teachers design lesson plans, unit plans, and a year-long plan throughout the three-semester internship and student teaching seminar. Specific science teacher preparation standards are addressed with assignments to build a conceptual bridge between the theoretical basis and instructional strategies taught in the methods course and practical experiences gained in the internship. During the first methods course, teacher interns: (a) question and analyze specific components of their teaching with a lesson study (Lewis, 1995); (b) begin lesson- and unit-level planning and investigate curricular construction within their discipline; (c) develop and teach inquiry-based lessons; (d) interview secondary students about common misconceptions; and (e) complete a science safety course. The second methods course emphasizes scientific discourse practices, educative assessment, and long-term planning. The concurrent internship provides opportunities to experience and explore curricular and instructional decisions by planning and enacting lessons with an experienced teacher. Together, teaching methods courses, internships, and the student teaching seminar form a "central spine" for the science teacher education program.

Clinical Teaching Experiences

Teacher interns complete a three-phase, 650-hour internship in which they assume greater responsibility for teaching from phase to phase. In Phase 1, undergraduate students complete an internship during the spring semester in junior year, and MAT students are in summer school and science camp settings (Table 4.3). Interns co-teach, explore student misconceptions, and interview students about specific science topics. In Phase 2 teacher interns in both programs spend 10 hours per week in formal classroom

TABLE 4.3 Science Teaching Methods, Internship, and Student Teaching Sequence With Additional MAT Focus on Teacher Action Research Project

Phase 1	Phase 2	Phase 3
BS: Spring semester during normal school year. MAT: Summer school, science camp sessions.	BS and MAT placements in fall semester during normal school year and in the same course section.	BS and MAT student teaching placements in spring semester.
5-week, 50 hours	15-week, 150 hours	15-week, 450 hours
Focus: Science safety, students' ideas about science interviews, lesson planning, lesson study, and sketch broad ideas of one curricular unit.	*Focus:* Planning and enacting curriculum and instruction, lesson and unit planning with greater emphasis on formative assessment practices and supporting science discourse. *Teacher Action Research Coursework* (MAT only): MAT teacher candidates learn about different educational research approaches, including teacher action research. Course culminates in writing a teacher action research proposal to do during the student teaching.	*Focus:* Student teachers have an 80% full-time teaching load for the semester: four classes if short periods, and two classes if longer periods in a block schedule is used. *Teacher Action Research Coursework* (MAT only): As student teaching starts the MAT teacher candidates make minor adjustments as necessary to their research plan. They collect data to address their research questions and preliminary analysis.

settings, plan and teach science lessons, conduct a lesson study, and design unit-level curriculum. In Phase 3, interns become student teachers. Student teachers teach two courses, a total of four sections, and have two preparation periods.

Interns are rotated to new cooperating teachers from phase to phase to provide experience with different teaching approaches in settings with diverse student populations, middle and high schools in urban, suburban, and sometimes rural districts, and different endorsement subjects. Teaching interns experience working with students of different abilities, planning and teaching science lessons that include accommodations for students with special needs, developing classroom management skills, generating assessment plans and instruments, and working in professional learning communities. Each teaching internship is unique due to varying settings, cooperating teachers, grade level and science content; however, basic components of the coursework are consistent (Table 4.3).

METHODOLOGY

We used a longitudinal, exploratory, multi-method approach to investigate beginning science teachers' subject matter knowledge, science misconceptions, self-efficacy, and instructional practices in two TPPs. We provide research questions, specific data sources, and methods for each part of the study as follows.

Research Questions

The main research questions we investigated were:

1. What are the common discipline-specific misconceptions of teacher candidates and other undergraduates who take science courses with a range of SMK?
2. What is the minimum amount of SMK needed to avert common science misconceptions in chemistry, physics, and middle-school life science?
3. What is the self-efficacy of beginning science teachers who completed a graduate level preparation program and how does it change during their first 3 years of teaching?
4. To what degree are the instructional practices of science teachers with a range of SMK inquiry-based? How does inquiry-based instruction compare over time among science teachers who completed undergraduate and graduate level preparation programs?

Methods

In the following subsections, we provide descriptions of the data sets and analytic methods used to address the research questions. Sample sizes are presented along with findings for some analyses. We refer readers to other reports (Lewis, Rivero, Lucas, Musson, & Helding, under review; Lewis, Rivero, Lucas, Tankersley, & Helding, 2018) for greater in-depth presentation and discussion of our research projects due to a lack of space here to provide full analytic details.

Subject Matter Knowledge and Misconceptions Methods

Subject matter knowledge was examined through an analysis of Misconceptions-Oriented Standards-Based Assessment Resources for Teachers (MOSART) test scores and transcript analysis. MOSART scores are based on multiple-choice tests that assess students' understanding of science concepts. We used the MOSART chemistry (9–12), physics (9–12), and life science (5–8)[3] tests (Sadler et al., 2010). The preservice teachers in the undergraduate and MAT programs took the tests at the end of their program after student teaching. We obtained participant transcripts and analyzed courses taken,[4] number of credit hours, and GPA earned in the categories of life science, chemistry, physics, and Earth science. We report descriptive statistics with each content area analysis. Using an approach outlined by Miles, Huberman, and Saldaña (2014), for each of the subject area analyses, we divided participants into four categorical groups based on the amount of credit hours taken in each subject (i.e., chemistry, life science, physics): (a) Group 1 = 0–8; (b) Group 2 = 9–16; (c) Group 3 = 17–24; and (d) Group 4 = 25 or more. We determined each group's average test score and compared these with the recommended passing score and tallied items for persistent misconceptions. Finally, we analyzed course transcripts to identify courses commonly taken by participants in each of the four groups.

To identify possible SMK predictors, we regressed participants' GPA and science credit hours on the corresponding MOSART test scores. When examining participants' SMK, we used two primary outcome measures for each content area: (a) MOSART test scores and (b) that same MOSART test score transformed into a pass/fail or binary outcome. The MOSART test developers' recommended cutoff for a passing score is 80%. Thus, we recorded scores equal to or above 80% as passing scores and below as failing scores. We also coded sex to investigate if there were any differences between male and female test takers' performances on the tests.

Teacher Self-Efficacy Methods

We evaluated MAT program graduates at the end of their student teaching (ST, $n = 41$) and each year thereafter (Y1, $n = 24$; Y2, $n = 20$; Y3, $n = 8$). We used the *Teacher Sense of Efficacy Scale* (TSES), a 24-item survey instrument with a 5-point scale developed by Tschannen-Moran and Hoy (2001), to investigate teachers' self-efficacy in three areas: (a) student engagement, (b) classroom management, and (c) instructional strategies. We examined teacher self-efficacy using a multivariate analysis of variance (MANOVA). Our outcome variables were the instrument's three subscales. We used number of years of teaching experience to predict change across the multiple outcome measures.

Longitudinal Study Methods

We conducted a 4-year longitudinal study of five cohorts of master's level science teacher education program graduates (Lewis, Rivero, Musson, Lu, & Lucas, 2016). We coded and analyzed science lessons from student teaching to fifth year post-program to describe teachers' enacted practices, and administered annual surveys of teacher self-efficacy and beliefs about

TABLE 4.4 Number of Lessons by Years of Teaching Experience (2015–2016 and 2016–2017 Data)

Program	Student Teaching	1	2	3	4	5	Total
MAT	28	68	74	81	53	24	**328**
Undergraduate	32	41	45	23	12	6	**159**
Total	**60**	**109**	**119**	**104**	**65**	**30**	**487**

TABLE 4.5 Number of Teachers by Years of Teaching Experience (2015–2016 and 2016–2017 Data)

Program	Student Teaching	1	2	3	4	5	Total
MAT	10	13	11	14	10	4	**62**
Undergraduate	16	8	9	9	2	1	**45**
Total	**26**	**21**	**20**	**23**	**12**	**5**	**107**

reform-based science teaching (Lucas & Lewis, 2017). For the study's second 2 years (academic years 2015–2016 and 2016–2017), we also coded science lessons of a comparison group of teachers from our undergraduate secondary science TPP (Table 4.4). For these 487 lessons (Table 4.5), we coded the lessons using two instruments, the Electronic Quality of Inquiry Protocol (EQUIP) instrument (Marshall, Horton, Smart, & Llewellyn, 2009) and the Discourse in Inquiry Science Classrooms (DiISC; Baker, et al., 2008) to measure the quality of inquiry-based instruction.

RESULTS

Subject Matter Knowledge and Misconceptions by Discipline

In our analysis of inquiry-based practices, we tried to determine how much SMK was necessary for beginning teachers to teach reform-based science lessons. First, we needed to determine teachers' SMK with a range of science coursework and any persistent misconceptions (Research Question #1). Therefore, we analyzed participants' transcript information for common undergraduate science coursework to compare with their scores on the domain-specific science misconceptions tests (MOSART). Based on a conceptual change model, we considered participants' misconceptions as an outcome of the SMK domain. Our premise was that the fewer misconceptions a secondary science teacher held, the better prepared the teacher should be to teach inquiry-based science. We present the results in three sections, one for each of the three disciplines.[5]

Chemistry

To analyze chemistry knowledge, we used a sample of 97 participants, from three groups: (a) preservice MAT teachers ($n = 44$) with at least an undergraduate degree in science, (b) preservice undergraduate secondary science teachers ($n = 31$), and (c) undergraduate students ($n = 22$) pursuing minors and majors in chemistry. We divided all participants into four groups based upon the amount of chemistry coursework taken at the time of the test. We calculated the average and standard deviation for both chemistry hours and chemistry GPA, tallied the common chemistry coursework for each group, and compared these three variables with the MOSART test scores (Table 4.6). Using the MOSART chemistry (9–12) test scores for each group, we identified items with less than an average of 50% correct responses as persistent misconceptions and concluded that there were few or no misconceptions for those items with an average of 90% or more correct responses.

Qualitative Analysis of Chemistry SMK

As shown in Table 4.6, we observed that with increasing chemistry coursework, participants had fewer misconceptions. For example, Group 4 with more than 25 credit hours had 10 correct concepts, while Group 1 only had three correct concepts. Moreover, we could only identify one misconception in Group 4, while we identified seven misconceptions in Group 1.

The two topics with the most persistent misconceptions, appearing in all four groups, were chemical bonding and nuclear processes. When considering participants' chemistry coursework, we found that advanced chemistry coursework, such as physical chemistry or organic chemistry, still did not seem to help test takers to overcome misconceptions about metallic bonding. In a review of a general chemistry college textbook (Brown, LeMay, Bursten, & Murphy, 2008), only two paragraphs were devoted to metallic bonding in the chapter on chemical bonding. Metallic bonding would probably only be addressed in any depth in an inorganic chemistry course. Only those with more than 25 credit hours of chemistry had a higher percentage of correct responses. Easier items on the chemistry test concerned periodicity and questions about atomic particles. These had the highest percentages of correct answers overall. Most participants had taken *General Chemistry I* and *II* courses (93% and 88%, respectively). The content covered in those courses appeared to facilitate a basic understanding of atomic particles, content, and arrangement of the periodic table. Groups with introductory levels of chemistry SMK showed an average score for Group 1 at 65% compared with an average passing score of 88% for high levels of chemistry SMK (Group 4). Teachers with 9–16 credit hours of chemistry coursework (e.g., including organic chemistry) had, on average, better results ($M = 74\%$) and held fewer misconceptions than those with

TABLE 4.6 Science Teachers' Chemistry Credit Hours, GPA, Coursework Commonly Taken, and MOSART Test Results

Group	Commonly Taken Coursework	Credit Hours M (*SD*)	GPA M (*SD*)	MOSART Test Score (%) M (*SD*)	Number of Items With Misconceptions[a]	Number of Items With Few Misconceptions[b]
Group 1 (*n* = 10)	General Chemistry I	8 (1)	2.8 (0.6)	65 (15)	7	3
	General Chemistry II					
Group 2 (*n* = 65)	General Chemistry I	13 (2)	3.3 (0.6)	74 (15)	3	2
	General Chemistry II					
	Organic Chemistry I					
Group 3 (*n* = 11)	General Chemistry I	21 (2)	3.3 (0.4)	77 (11)	3	5
	General Chemistry II					
	Organic Chemistry I					
	Organic Chemistry II					
	Organic Chemistry Lab					
Group 4 (*n* = 11)	General Chemistry I	41 (17)	3.2 (0.4)	88 (10)	1	10
	General Chemistry II					
	Organic Chemistry I					
	Organic Chemistry II					
	Organic Chemistry Lab					
	Inorganic Chemistry					
	Physical Chemistry					
All (*n* = 97)	General Chemistry I	16 (11)	3.2 (0.6)	75 (15)	2	2
	General Chemistry II					
	Organic Chemistry I					

[a] Less than 50% of group gave correct responses.
[b] More than 90% of group gave correct responses.

just two general chemistry courses. However, only Group 4 reliably passed the test (Lewis et al., 2018).

Quantitative Analysis of Chemistry Subject Matter Knowledge

We also conducted an analysis to identify variables that contributed significantly to the SMK outcome measure (Table 4.7). Considering the variability associated with MOSART chemistry test scores, chemistry coursework GPA uniquely accounted for 27% of that variance ($\beta = 0.32$, $t = 2.99$, $p < 0.01$), number of chemistry credit hours uniquely accounted for 28% of that variance ($\beta = 0.29$, $t = 3.16$, $p < 0.01$), and physics coursework GPA uniquely accounted for 24% of that variance ($\beta = 0.28$, $t = 2.66$, $p = 0.01$). For each 0.10 increase in chemistry GPA, participants were 1.22 times more likely to pass the test ($e^{\beta} = 7.47$). Empirically, the regression model suggests that a minimum of 30 chemistry credit hours and an average chemistry GPA of 3.21 were associated with an average score on the MOSART chemistry test of 80% or better (i.e., passing).

Physics and Physical Science

We recruited preservice science teachers ($n = 70$) and undergraduate physics students ($n = 21$) to take the MOSART physics (9–12) test (Sadler et al., 2010), examined course transcripts of all physics test takers, and created four groups based upon physics credit hours. The analytic approach was identical to the approach with the chemistry test data.

TABLE 4.7 Descriptive Statistics for the MOSART Chemistry (9–12) Test

Predictor	Mean (or Mode where indicated)	σ	*n*
MOSART chemistry score	75.41	15.11	105
Pass/Fail (1/0) MOSART score	0 (mode)	n/a	105
Pass			47 (44.3%)
Fail			58 (55.2%)
Sex of participant	1 (mode)	n/a	101
Male			37 (36.6%)
Female			64 (63.4%)
Delay between last coursework and test (years)	2.63	5.38	105
Total number of credit hours of chemistry coursework	16.65	11.42	105
Chemistry coursework GPA	3.21	0.56	104
Total number of credit hours of physics coursework	9.22	8.68	104
Physics coursework GPA	3.11	0.56	85

Qualitative Analysis of Physics Subject Matter Knowledge

We found that the number of physics credit hours was positively correlated with MOSART scores (Table 4.8). For instance, 23 out of 25 items (92%) on the physics test appeared to be easier for Group 4 as compared to Group 1, who performed well on only six of 25 items (24%). Similarly, test takers with at least 17 physics credit hours exhibited few or no misconceptions on topics with which their counterparts with less than 17 credit hours struggled (i.e., items on which at least 50% of participants answered incorrectly). On average, Groups 1 and 2 participants with less than 17 credit hours did not meet the 80% passing score for the physics test. In our analyses of physics courses taken, we also observed that participants with less than 9 credit hours usually took algebra-based or descriptive introductory physics courses, which are less mathematically rigorous as compared to calculus-based introductory physics courses taken by participants with at least 17 credit hours. While participants with at least 17 credit hours were more likely to pass the physics test, the type of introductory physics courses taken by participants may have influenced their test performance.

Courses taken by the participants provide insight into their physics misconceptions. For instance, Group 1 participants mainly took one general physics course (i.e., *General Physics I*) that only includes topics in mechanics, heat, waves, and sound. Concepts in electricity, magnetism, optics, relativity, atomic and nuclear physics are commonly included in *General Physics II*. Analysis of items correctly answered by each group showed that Group 1 participants had persistent misconceptions on electromagnetic waves, electromagnetism, and quantization of energy, which are topics addressed in the *General Physics II* course. The test also surprisingly revealed that Group 1 participants still held persistent misconceptions on Newton's laws of motion and wave properties, even though these topics are taught in *General Physics I*.

Similar to Group 1, Group 2 participants with a range of 9–16 credit hours also appeared to struggle with electromagnetism and modern physics concepts. Misconceptions with Newton's laws of motion and wave properties persisted among Group 2 participants despite having a greater range of introductory physics courses than Group 1. These results suggest that taking fewer than 17 credit hours of physics courses is insufficient for preservice teachers to develop the content knowledge needed to teach a high school physics course.

Quantitative analysis of physics SMK. We used multiple variable regression using each of the six predictors listed in Table 4.9 to predict the MOSART physics (9–12), and a logistic regression for the pass/fail scores, using the same predictors.

Physics and chemistry coursework, specifically credit hours and GPA, and (unlike the other subject areas we investigated) teachers' sex had a

TABLE 4.8 Science Teachers' Physics Credit Hours, GPA, Commonly Taken Coursework, and MOSART Test Results

Group	Commonly Taken Coursework	Credit Hours M (*SD*)	GPA M (*SD*)	MOSART Test Score (%) M (*SD*)	Number of Items With Misconceptions[a]	Number of Items With Few Misconceptions[b]
Group 1 ($n = 25$)	General Physics I	5 (2)	2.77 (0.70)	67 (17)	7	6
	General Physics I Lab					
Group 2 ($n = 48$)	General Physics I	11 (2)	3.25 (0.50)	70 (13)	8	8
	General Physics I Lab					
	General Physics II					
	General Physics Lab II					
	General Physics III					
	Elements of Electrical Engineering					
Group 3 ($n = 8$)	General Physics I	23 (3)	3.17 (0.40)	85 (10)	0	8
	General Physics Lab I					
	General Physics II					
	General Physics Lab II					
	General Physics III					
	General Physics Lab III					
	Physics and Astronomy					
	Mathematics					
	Lasers and Optics					
	Concepts in Modern Physics					

(continued)

TABLE 4.8 Science Teachers' Physics Credit Hours, GPA, Commonly Taken Coursework, and MOSART Test Results (continued)

Group	Commonly Taken Coursework	Credit Hours M (*SD*)	GPA M (*SD*)	MOSART Test Score (%) M (*SD*)	Number of Items With Misconceptions*	Number of Items With few Misconceptions**
Group 4 ($n = 10$)	General Physics I	48 (15)	3.39 (0.36)	90 (6)	2	23
	General Physics II					
	General Physics II					
	General Physics Lab I					
	General Physics Lab					
	II General Physics					
	Lab III					
	Physics and Astronomy					
	Electrical and Electronic Circuits					
	Mechanics					
	Thermal Physics					
	Experimental Physics I					
	Electromagnetic Theory					
	Quantum Mechanics					
	Optics and Electromagnetic Waves					
Total ($n = 91$)	General Physics I	12 (9)	3.12 (0.58)	73 (15)	4	8
	General Physics I Lab					
	General Physics II					

[a] Less than 50% of group gave correct responses.
[b] More than 90% of group gave correct responses.

TABLE 4.9 Descriptive Statistics for the MOSART Physics (9–12) Test

Predictor	Mean (or Mode where indicated)	σ	*n*
MOSART physics score	72.75	15.44	97
Pass/Fail (1/0) MOSART score	0 (mode)	n/a	97
Pass			42 (43.3%)
Fail			55 (56.7%)
Sex of participant	1 (mode)	n/a	97
Male			49 (50.5%)
Female			48 (49.5%)
Delay between last coursework and test (years)	2.52	5.46	97
Total number of credit hours of chemistry coursework	13.35	11.65	97
Chemistry coursework GPA	3.13	0.64	86
Total number of credit hours of physics coursework	13.13	11.11	97
Physics coursework GPA	3.15	0.58	94

Note: A number of undergraduate physics students had not taken any chemistry coursework, which was correctly coded as 0 total credit hours, but then resulted in no GPA. Thus in the category of GPA it appears as if there is missing data, but in these cases GPA does not exist.

statistically predicted MOSART scores. Because the content in this case was physics, we chose physics coursework GPA, number of physics credit hours, and sex as the predictors in the final model. Specifically, physics coursework GPA uniquely accounted for 34% of the variance in MOSART physics test scores ($\beta = 0.35$, $t = 4.10$, $p < 0.01$) and number of physics credit hours uniquely accounted for 31% of that variance ($\beta = 0.33$, $t = 3.64$, $p < 0.01$); the relationship between both physics GPA and hours of coursework and MOSART physics test scores was positive. Sex uniquely accounted for 19% of that variance ($\beta = -0.20$, $t = 2.28$, $p = 0.03$). The relationship between sex and MOSART physics test scores, however, was negative. That is, female participants tended to score lower than male participants, although we suspect that this was an artifact of having few women with more credit hours in physics in the sample. Because our sample of participants did not have enough women with high numbers of physics credit hours, we were not able to run an analysis that included both sex and the minimum credit hours to predict a passing score on the test.[6] In our final analysis, each additional credit hour of physics coursework significantly increased the likelihood of an individual passing the MOSART physics test by 19% ($e^{\beta} = 1.19$).

Life Science

For the middle-school life science SMK analysis, we examined participants ($n = 72$) from the two TPPs. Unlike the other subject areas we were sufficiently powered with the preservice teacher test takers and did not recruit any life science majors to take the test. The analytic approach was identical to the approach with the chemistry test data.

Qualitative analysis of preservice teachers' life science SMK. In grouping the preservice teachers' SMK into four categories, all four groups had average scores over the 80% passing score. Group 1 not only had the lowest average score at 83%, but 50% of this group ($n = 8$) also scored under the 80% cutoff score (Table 4.10). The easiest items for all four groups concerned energy movement in an ecosystem. Participants in Groups 1 and 2 exhibited misconceptions about cell specialization and population growth and carrying capacity. Groups 1 and 3 scored less than 80% on items related to population dynamics as well. Group 2 had an average of 86% on the standard associated with population dynamics. Group 2 did not have any individuals that missed all three questions for this standard, but Groups 1 and 3 did. Even Group 3 showed misconceptions in four critical standards: (a) cell specialization, (b) population dynamics, (c) population growth and carrying capacity, and (d) disease. The confusion with these ecological concepts is not surprising due to the lack of an ecology course in the list of common courses taken by Group 3. While Group 4 participants on average did not have a much higher MOSART score than Groups 2 or 3, Group 4 did not show any persistent misconceptions. Group 4 had the greatest number of different courses and life science electives beyond general biology; the variety of classes taken by Group 4 may have been what led to the lack of persistent misconceptions identified by the test despite the average for Group 4 (90%) only being slightly above the average for Group 2 (89%).

Quantitative Analysis of Preservice Teachers' Life Science SMK. We used multiple regression with four predictors of the middle school MOSART (5–8) life science test score and a logistic regression using the same possible prediction of the probability of a teacher pass/fail test score. Descriptive statistics are presented in Table 4.11. Biology coursework accounted for 12.4% of the variance in MOSART test scores ($R^2 = 0.12$), with a positive relationship of 0.35 ($\beta = 0.35$). Thus, as preservice science teachers took more college-level biology credit hours, their MOSART test scores, on average, increased. Additionally, for each credit hour of biology a teacher

TABLE 4.10 Science Teachers' Biology Credit Hours, GPA, Coursework Commonly Taken, and MOSART Test Results

Group	Coursework Commonly Taken	Credit Hours M (*SD*)	GPA M (*SD*)	MOSART Test Score (%) M (*SD*)	Number of Items With Misconceptions[a]	Number of Items With few Misconceptions[b]
Group 1 ($n = 8$)	General Biology	4.5 (2.6)	3.9 (0.5)	83 (6)	8	3
	Principles of Ecology					
	Elements of Biochemistry and Lab					
Group 2 ($n = 12$)	General Biology	12.25 (2.3)	3.2 (0.5)	89 (7)	2	6
	General Biology Lab					
	Principles of Ecology					
	Ecology Lab					
	Elements of Biochemistry and Lab					
Group 3 ($n = 21$)	General Biology	23.4 (1.5)	3.45 (0.3)	86 (7)	4	1
	General Biology Lab					
	General Botany					
	Human Physiology					
	Human Physiology Lab					
	Microbiology					
	Microbiology Lab					
	Introduction to Zoology and Lab					
Group 4 ($n = 31$)	Cell Structure and Function	36.4 (10.8)	3.3 (0.5)	90 (7)	0	3
	Organismic Biology					
	General Genetics					
	Principles of Ecology					
	Microbiology					
	Microbiology Lab					
Total ($n = 72$)		24.6 (12.6)	3.4 (0.5)	88 (7)	3.5	3.4

[a] Less than 80% of group gave correct responses.
[b] More than 98% of group gave correct responses.

TABLE 4.11 Predictors and Descriptive Statistics for MOSART Life Science (6–8) Test

Predictor	Mean (or Mode where noted)	σ	n
MOSART Life Science score	88.96	7.01	83
Pass/Fail MOSART test score	1 (mode)	n/a	83
Pass		n/a	76 (91.6%)
Fail		n/a	7 (8.4%)
Sex of Participant	1 (mode)	n/a	83
Male		n/a	37 (44.5%)
Female		n/a	46 (55.4%)
Delay between last coursework and test (years)	3.34	5.92	83
Total number of credit hours of biology coursework	28.44	15.63	83
Biology coursework GPA	3.40	0.45	83

earned, the odds of passing the life science MOSART test increased by 9.8% ($e^{\beta} = 1.098$).

Teacher Self-Efficacy

In response to Research Question #3, we examined MAT teachers' self-efficacy using a multivariate analysis of variance (MANOVA). Our three outcome variables were the three subscales on the self-efficacy instrument, regarding: (a) student engagement, (b) instructional strategies, and (c) classroom management (Table 4.12). We used number of years of teaching experience to predict change across the multiple outcome measures. Time

TABLE 4.12 Average Teacher Self-Efficacy of MAT Graduates

	Post-Student Teaching	Post-Year 1	Post-Year 2	Post-Year 3
Number of teachers	41	24	20	8
Student Engagement Mean*	3.84	3.54	3.49	3.56
SD	0.46	0.36	0.35	0.39
Classroom Management Mean	4.05	3.76	3.84	3.97
SD	0.42	0.37	0.34	0.39
Instructional Strategies Mean*	4.15	3.94	4.01	3.92
SD	0.49	0.47	0.51	0.50

* statistically significant difference when $p < 0.05$ level.

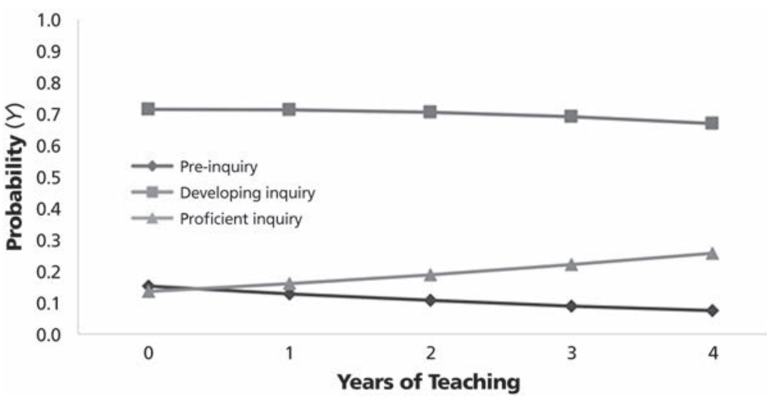
spent teaching accounted for average differences across the three measures, Wilk's Lambda $(9, 211) = 2.02$, $p = 0.04$. In follow-up tests using a Bonferonni adjustment, we found statistically significant changes over all available time points on self-efficacy related to student engagement ($F(3, 89) = 4.54$, $p < 0.01$) and instructional strategies ($F(3, 89) = 3.17$, $p = 0.03$), but not classroom management ($F(3, 89) = 1.18$, $p = 0.32$) subscales.

Pairwise comparisons indicated statistically significant changes between Years 1 and 2 of teaching for self-efficacy related to student engagement, and between student teaching and Year 1 of teaching for self-efficacy related to instructional strategies. This indicated a complex relationship between the subscale scores and teaching experience. This was complicated by potential measurement issues and underpowered tests. We resolved this matter by concluding that the relationship between scales, subscales, and time points within scales and subscales needs to be further analyzed and otherwise becomes too complex to be practical. To summarize, the number of years a teacher taught mattered when predicting overall self-efficacy and specifically for self-efficacy associated with student engagement and instructional strategies. It is important to note that longitudinal comparisons were only meaningful when we used the teachers as their own controls (i.e., we treated the data from the first time they took the survey after they finished the TPP as a baseline measure). This suggested that either self-efficacy had stabilized or the measurement instrument was not sensitive to changes in self-efficacy after two or more years of having exited the MAT program. Over time, MAT teachers who persisted through the induction period maintained a generally positive outlook on their own agency (i.e., they perceived they could do "some" to "quite a bit" to affect positive change) in these three teaching areas.

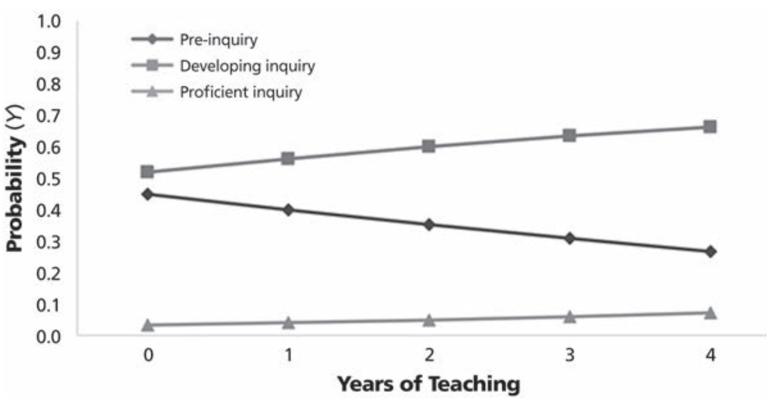
Beginning Science Teachers' Enacted Practices Using Inquiry-Based Instruction

A major goal of our longitudinal study was to investigate the impact of observation-level variables (i.e., time, level of observed lesson [high school vs. middle school], length of observed lesson, and mode of observation [video vs. real-time] and teacher-level characteristics [i.e., teacher's sex and education program]) on the likelihood of an observed science lesson being at or below a certain level of inquiry (i.e., pre-inquiry, developing, proficient, or exemplary) on the EQUIP instrument, our measure of inquiry-based instruction. In response to Research Question 4, we used 455 classroom observations from four academic years of data (2012–2013 to 2015–2016) of 51 science teachers' lessons from both programs. Hierarchical generalized linear models were built to investigate the relationship between level of inquiry-based instruction and the predictor variables at both levels. For more meaningful interpretation, we calculated the corresponding predicted probabilities for observed lessons taught by teachers in the two different preparation programs and controlled for other observation- and teacher-level characteristics. This allowed us to plot the probability of a lesson employing a particular level of inquiry-based instruction across years of teaching. Figure 4.2 shows the change in probability for science lessons taught by teacher graduates of the two TPPs (Lucas & Lewis, 2017).

Among teacher-level characteristics, only the teacher preparation program was found to be statistically significant. Compared to teachers from



(a)



(b)

Figure 4.2 Change in probability of an observed science lesson being at or below a proficiency level of inquiry-based instruction across years of teaching: (a) teacher has a master's degree in science teaching; and (b) teacher has a bachelor's degree in secondary science education (from Lucas & Lewis, 2017).

the undergraduate TPP, MAT teachers appeared to show more rapid growth in their use of inquiry-based teaching practices. Using a ratio of –2LL statistics, we determined that the likelihood of an observed lesson having no use of inquiry-based instruction (e.g., lecture-based) was significantly lower for MAT teachers than the undergraduate TPP. These findings imply that program differences affect the development of inquiry practices. For example, a beginning MAT teacher with 1 year of teaching experience had about a 13% chance of teaching through more traditional methods, while an undergraduate TPP teacher had a likelihood of 40% of doing so. Additionally, over the induction period MAT teachers taught lessons at the proficient inquiry level at twice the rate of undergraduate teachers.

Changes in Teachers' Use of Inquiry-Based Science Instruction

Along with our model building of teachers' use of inquiry-based instruction, when we reviewed our MAT program data set on the four specific areas of inquiry-based teaching on the EQUIP instrument (i.e., instructional, discourse, assessment, and curriculum factors) we found particular patterns of growth and areas of challenge. Growth, or lack thereof, in these areas can be considered to be a result of teachers acquiring teaching experience without much professional development, as teachers reported that they were mainly in survival mode and had little time to do anything but teach. We identified four areas of growth as teachers gained experience: (a) teaching for knowledge acquisition, (b) questioning level they employed (i.e., asking more questions that required critical thinking), (c) conceptual development of science concepts, and (d) content depth. Encouragingly, all four of these aspects of teaching science were strongly addressed during the teacher education program and appeared to support teachers' growth during the induction period without much additional formal professional development. Alternatively, some areas of little or no discernable growth included teachers: (a) using an inquiry-based order of instruction, specifically with student exploration preceding explaining; (b) promoting classroom interactions through discourse; (c) accessing students' prior knowledge for use in revising instruction; and (d) positioning learner centrality in the enacted curriculum.

Subject Matter Knowledge Relationship With Inquiry-Based Instruction

Chemistry Lessons

We examined the variability associated with observations of high-school chemistry lessons, using the DiISC and EQUIP observation instruments to assess 13 teachers with 63 lessons. The mean chemistry credit hours was

24.95 ($SD = 2.16$); the mean physics credit hours was 9.62 ($SD = 0.45$). We only used six items on the DiISC that focused on inquiry-based teaching practices as a single factor, but used all EQUIP items grouped into two factors. Using a multivariate analyses (i.e., MANOVA), we found that teachers' total number of chemistry credit hours predicted inquiry-based instruction ($F(3, 59) = 4.60$, $p < 0.01$). Thus, the more chemistry credit hours a teacher had, the more inquiry-based the lesson tended to be. In predicting inquiry-based teaching practices, total number of chemistry credit hours accounted for 19% of the variance (*partial* $\eta^2 = 0.190$). We also noted that total number of physics credit hours was statistically significant as a predictor alone ($F(2, 59) = 4.60$, $p < 0.01$), but not in the same model with chemistry credit hours ($F(3, 58) = 2.06$, $p = 0.12$).

Physical Science Lessons

We examined the variability associated with middle- and high-school physical science lessons using observations of 88 lessons taught by 28 teachers (Table 4.13). Using the factor scores from the EQUIP and DiISC, we used multivariate analyses (MANOVA) with three independent variables (TPP, teaching experience, total science GPA), and three dependent variables (EQUIP Factor 1 score on discourse and assessment, EQUIP Factor 2 score on instructional strategies and curricular choices, and DiISC inquiry scale).[7] Total science GPA had a statistically significant relationship with the combined dependent variables, $F(3, 82) = 3.589$, $p < .05$, Wilk's Lambda = 0.884, *partial* $\eta^2 = 0.116$. Thus, a teacher's average weighted GPA in all science courses was associated with inquiry-based instruction in physical science lessons; the higher the total science GPA, the more inquiry-based the lesson tended to be.

We performed follow-up univariate ANOVAs with a Bonferroni adjustment to examine the main effect of total science GPA. Total science GPA had a significant relationship with EQUIP Factor 1 score (i.e., discourse and assessment; $F(1, 84) = 8.936$, $p < 0.0167$, *partial* $\eta^2 = 0.096$), but not with EQUIP Factor 2 score (i.e., instructional strategies and curricular

TABLE 4.13 Descriptive Data Associated With Physical Science Teachers' Inquiry-Based Instruction

Variable	*N* (%)	Mean	*SD*
Number of teachers	28		
Number of lessons	88		
BA	14 (16%)		
MA	74 (84%)		
Total science GPA		3.43	0.33
Teaching experience (in days)		364.80	187.04

choices; $F(1, 84) = 2.215$, $p = 0.140$, *partial* $\eta^2 = 0.026$) or the DiISC inquiry score ($F(1, 84) = 0.327$, $p = 0.569$, *partial* $\eta^2 = 0.004$). Thus, averaging across TPPs and teaching experience, the higher the total science GPA of a physical science teacher, the more inquiry-based the discourse and assessment practices tended to be in a lesson.

Life Science Lessons

Using the same analytic approach as we adopted for the chemistry and physical science lessons, we examined the variability associated with 178 middle-school life science and high-school biology lessons taught by 51 teachers (Table 4.14). Of the 178 lessons, the most common lessons taught were on: (a) genetics and heredity (17%), (b) disease and the human body (16%), (c) organisms (14%), and (c) evolution and biodiversity (10%). Using MANOVA, we found a significant relationship between three predictors and the level of inquiry-based science lessons by these teachers: (a) total number of science credit hours, $F(3, 157) = 3.87$, $p = 0.01$; (b) Earth and space science GPA, $F(3, 157) = 3.10$, $p = 0.01$; and (c) middle- or high-school classroom, $F(3, 157) = 4.15$, $p < 0.01$ with high school teachers outperforming middle school teachers.

Using teachers' SMK variables and teaching level to predict their inquiry-based teaching practices in life science and biology lessons, we found the following effect sizes: (a) total number of science credit hours uniquely accounted for 6.9% of the variance (*partial* $\eta^2 = 0.069$); (b) Earth and space science GPA uniquely accounted for 5.6% of the variance (*partial* $\eta^2 = 0.056$); and (c) middle or high school uniquely accounted for 7.4% of the variance (*partial* $\eta^2 = 0.074$), that is, high school biology teachers used more inquiry-based approaches than middle school teachers.

TABLE 4.14 Descriptive Data Associated With Life Science Teachers' Inquiry-Based Instruction

Factor	*N* (%)	Mean	*SD*
Number of teachers	51		
Number of lessons	178		
BA	39 (22%)		
MA	139 (78%)		
Total science credit hours		68.55	1.05
Earth and space credit hours		75.22	1.45
Number of middle school lessons	49 (28%)		
Number of high school lessons	164 (72%)		

DISCUSSION

Subject Matter Knowledge, Misconceptions, and Connections to Teaching

The MOSART chemistry (9–12) and physics (9–12) tests were originally designed as diagnostic tools for teachers to use with high school chemistry and physics students at the beginning of those courses, while the MOSART life science (5–8) test was designed to address common misconceptions at the middle-school level. We used these tests as measures of teachers' SMK to correlate with coursework completed in each discipline to determine the minimum amount of coursework and mastery level (i.e., GPA) that teachers would need to have to demonstrate competency within a discipline.

High School Chemistry

Interestingly, even though the curriculum of a standard high school chemistry course would be very similar to introductory coursework in chemistry, it took much more than two introductory college-level chemistry courses for participants to overcome common chemistry misconceptions. Study participants on average did not pass the MOSART chemistry (9–12) test, but there was great variability around a passing score of 80%. The analysis also revealed that the participants' chemistry GPA was a significant predictor of the likelihood of obtaining a passing score on the chemistry test. Thus, GPA in chemistry coursework is indicative of whether a teacher is likely to hold common chemistry misconceptions. When we showed the results to our two chemistry experts, they were not surprised to see the participants' common misconception in nuclear processes and explained that this topic was not commonly taught in undergraduate chemistry courses.

In terms of program design, we balanced the required minimum amount of science coursework in the state's teacher certification rules with the university guidelines for undergraduate degrees not to exceed a total of 120 credit hours. Therefore, students in our undergraduate TPP had, at most, only the minimum required number of 24 credit hours in one area of science. Because our analysis indicated that common misconceptions in chemistry could only reliably be overcome with 30 or more credit hours in chemistry, the undergraduate program (with the state-mandated minimum of 24 credit hours in chemistry) appears not to be rigorous enough to ensure that its teacher candidates' SMK was sufficient to avoid misconceptions about the content they must teach. Finally, when we investigated the relationship of teachers' SMK to the degree of inquiry used in their chemistry lessons, the total number of chemistry credit hours accounted for 19% of the variance in inquiry-based instruction. Thus SMK appears to make a real difference in the degree of teacher's use of inquiry-based teaching.

High School Physics and Physical Science

Study participants on average did not pass the MOSART physics (9–12) test. However, on average our test takers had taken only 13 credit hours in physics. The analysis also revealed that the participants' physics GPA was a significant predictor of a passing score on the MOSART physics test. Thus, both a greater number of physics credit hours and a higher physics GPA can be used to predict whether a teacher candidate is likely to avoid common physics misconceptions.[8] Most of the few physics-endorsed teachers in our sample came from our MAT program, who were all male and had at least an undergraduate degree in physics. These individuals had strong SMK and were well-prepared to teach both upper level high school physics and middle school or ninth-grade physical science courses. But most teachers who were teaching middle school and ninth-grade physical science lessons did so with few credit hours in physics (i.e., 4 to 12 credit hours). Thus, the majority of the lessons we observed were taught by teachers who had not achieved a passing score on the physics test. Previous studies (Hashweh, 2002; Murphy, 2005) have shown that teachers' SMK influences their planning for content instruction and use of explanatory representations. This also likely explained why teachers' physical science lessons tended to lack an inquiry-based approach to teaching science.

Middle School Life Science

Unlike our high school level physics and chemistry SMK results, study participants on average passed the MOSART life science (5–8) test. This is likely due to the much higher average number of life science credit hours (M = 28 credit hours) taken by the test takers as well as the fact that the middle school level test content was easier than that of the the MOSART physics and chemistry high school exams. However, despite easier middle school life science content, some misconceptions still persisted among teachers who had less than 25 life science credit hours. Although misconceptions persisted, most teachers with more than eight hours of life science credit hours passed the middle school MOSART life science (5–8) test, which suggests that they are qualified to teach these concepts. However, a biology teacher with more than 24 hours of life science credit hours would teach middle-school life science with fewer misconceptions.

Teacher preparation program designers should look at specific course requirements and gaps in undergraduate preservice teachers' life science knowledge. In our study, MAT teachers with an undergraduate degree in biological sciences had fewer middle-school life science misconceptions; without having administered the MOSART biology (9–12) test to enough participants we cannot comment at this time on the comparable minimum amount and mastery of SMK that would be necessary to teach high school biology.[9]

Teacher Self-Efficacy

As MAT teachers gained experience, their self-efficacy in the areas of student engagement and instructional strategies increased (Lewis et al., 2016). We suspect that the positive nature and stability of the MAT science teachers' self-efficacy during the induction period is related to strong SMK and a rigorous TPP that results in progressively more inquiry-based instruction in their classrooms. The more that teachers use reform-based curriculum and instruction that involves students using scientific practices that require active learning, the more engaged students are likely to be (Minner, Levy, & Century, 2010). The literature we reviewed in this chapter also claims that teachers with stronger SMK are potentially more capable of designing and adapting curriculum to reflect the nature of science within that particular discipline and teach using an inquiry-based stance.

Strengths and Challenges of Different Program Designs

As described in this chapter, our research has been situated within two programmatic designs for science teacher education, an undergraduate and a master's level program. There were limitations and benefits to each design in terms of developing teachers' SMK and education coursework and resulting pedagogical knowledge for teaching physical science. MAT teachers with a master's degree in science teaching showed higher initial use and faster growth in using inquiry-based teaching practices as compared to undergraduate teachers. However, when we tested undergraduate preservice teachers we found that on average, when they had about the same average amount of coursework and GPA, they tended to test slightly higher on the MOSART tests. This is likely because (a) they had taken their science courses more recently than the MAT teachers who may have been out of school for a period of time, and (b) that we had been able to control which science courses the undergraduate teachers had to take for certification because we had vetted the courses in advance. The latter was done to ensure that the science courses taken were the most aligned with what these future teachers were going to have to teach, whereas when MAT teachers applied to the program we reviewed their coursework and made accommodations for courses that were within the guidelines, but perhaps were not optimal for teaching aligned with secondary science education standards. While there were differences in the amount of science and education coursework between both programs, all teachers in the study took the same two science teaching methods courses. By treating these two courses as a static variable we chose to focus on identifying which science coursework specifically accounted for the amount of variance in those teachers who used more inquiry-based instruction.

RECOMMENDATIONS

Based upon our and other researchers' work in science teacher preparation (Loughran, 2014), we make recommendations in three critical areas of teacher preparation concerning: (a) TPP designers, (b) education researchers, and (c) policymakers and stakeholders.

Recommendations for Teacher Preparation Program Designers

In designing an effective TPP that went beyond minimal requirements for state certification, we not only ensured that the science teaching methods courses reflected the reform-based priorities for teaching science in the NGSS, but also attended to research on teaching diverse students to ensure that our MAT program design was aligned with best practices. Due to the maximum program credit hour restriction for undergraduate majors set by the university, we were unable to add a course in teaching ELLs without taking out another course, which was not feasible since all of their education coursework was necessary for certification. With the MAT program we had the freedom to include such a course because the MAT candidates were not taking science courses concurrently with teacher education certification courses. Teacher candidates who were career-changers tended to prefer shorter certification programs so that they could start working as soon as possible. Thus, we restricted admission to the program to those who had completed their science coursework as there were practical limits as to how much coursework could be completed within 14 months without sacrificing quality of learning. In summary, by optimizing both SMK and pedagogical knowledge development we have seen not only stronger beginning teaching practices by MAT graduates, but also higher rates of growth over time throughout the induction period, relative to teachers from the undergraduate program.

We found some disciplines more straightforward than others to determine which courses, and at what level, yielded the most aligned SMK for teaching science. We found that chemistry and physics had a more linear order to its scope and sequence than did the biological sciences and thus it is easier to recommend specific course work in chemistry and physics since there are fewer options. Additionally, those test takers who took a calculus-based physics course were generally stronger test takers, but these individuals also had greater than 17 credit hours in physics, thus were more squarely in-field than those who did not pass the MOSART physics test. The difference in algebra and calculus-based introductory physics courses may not matter as long as an individual persists in taking more physics courses, but it could also be a proxy for weaker math skills that are needed to perform well in physics.

Recommendations for Education Researchers

There is a need for more research in order to reliably determine how teachers' SMK relates to credit hours, associated GPA, and scores on discipline-specific comprehensive exams such as the Praxis II biology, chemistry, Earth science, and physics tests. However, there is also an equally strong argument to be made for more research to determine which education courses and types and hours of clinical placements contribute significantly to the variance seen among new science teachers in terms of reform-based classroom instruction with diverse students. In our research we found that while beginning teachers' science SMK was a significant contributor to inquiry-based teaching, it was clearly only part of the whole teacher preparation picture. More studies of beginning teachers are needed to identify the challenges of translating teacher learning in TPPs to classrooms, in particular in diverse classrooms (Cochran-Smith & Villegas, 2016; Carter & Darling-Hammond, 2016). In future analyses, we plan to examine the roles of in-service teacher professional development and teachers' beliefs about reform-based science teaching as well as science teaching in more and less diverse classrooms.

A second recommendation emerging from our study is in relation to research instruments and validation. The availability and use of validated instruments has been a perennial issue in studying teacher preparation and effective teaching. There is a need for research instruments that can bridge preservice and in-service teaching to facilitate longitudinal research. Some reliable instruments that have been developed are inappropriate for use with preservice teachers (e.g., Tschannen-Moran & Hoy, 2001) and thus make it difficult, for example, to track how teacher self-efficacy changes over time from TPP to experienced teacher. Additionally, some instruments take much calibration to use reliably (e.g., Reformed Teaching Observation Protocol; Piburn & Sawada, 2000; and EQUIP), which can be costly unless one has a well-funded research project, or were developed with particular projects in mind and thus adapting them for other purposes can potentially undermine instruments' consequential validity.

Implications for Policymakers and Stakeholders

Bybee (2011) argued that what science education needs now is a consistent system of coordinated purposes, policies, programs, and practice that can reduce the need for continually addressing inconsistencies. Part of that system must be a research-based set of standards for teacher certification. Our work has provided evidence that factors such as science content area credit hours, science GPA, and test scores are indicative of teachers' subject matter knowledge and possible misconceptions. Policymakers can leverage these and other findings to refine state guidelines for teacher certification to ensure that teachers are strongly prepared. For secondary science teachers, state departments of education that set teacher certification policy should consider making a careful distinction among specific science disciplines, as all sciences are not the same in their learning progressions, degree of linear accumulation of knowledge, and diversity of topics. Our study suggests that in chemistry, secondary science teachers need to take at least 30 credit hours in chemistry at a 3.2 GPA in order to pass a test of common chemistry misconceptions, but in physics the total number of credit hours could also include mathematics coursework (i.e., a minor degree). However, choice of coursework matters, as not all courses include the necessary science competencies that align with secondary science content standards.

CONCLUSION

To develop science teachers fluent in inquiry-based teaching approaches, TPPs should focus on elements such as building preservice teachers' self-efficacy and strong SMK, as well as opportunities to plan and practice lessons that elicit students' thinking and use of scientific practices. Additionally, it is important to prepare teachers in developing effective assessment practices and instructional strategies to explore and address students' misconceptions to generate more normative understanding and proficient achievement. Only 42% of middle-school and 49% of high-school science teachers have more than 10 years of teaching experience (Banilower et al., 2013), and schools with higher percentages of students who qualify for free and reduced lunch are more likely to have less experienced teachers than schools with fewer students in poverty (Banilower et al., 2013). It is more important than ever to ensure that newly certified teachers do not have significant deficiencies that will make their induction period unnecessarily challenging.

Science teacher preparation standards are essential, but in themselves insufficient to ensure that teacher education programs produce highly-qualified teachers. In an era of systemic science education reform, teacher education policies should be informed by careful, empirical research that demonstrates the relationships between teacher preparation factors, such as quantity of teacher SMK and mastery of such content to the quality of future science instruction. TPPs, state agencies, and national accreditors that attend to the research base and connect to the larger issues of science education reform, such as the performance expectations of the *Next Generation Science Standards* and models of reform-based science teaching, are far more likely to educate teachers who are prepared to teach all students in diverse settings and support more cohesive systems for teacher preparation.

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NOTES

1. U.S. Department of Education, Institute of Education Sciences, 2015 Science State Snapshot Report: Nebraska, retrieved from https://nces.ed.gov/nationsreportcard/subject/publications/stt2015/pdf/2016157NE8.pdf
2. In 2013, NCATE re-formed into the Council for the Accreditation of Educator Preparation (CAEP), which became one of UNL's several accreditors.
3. The MOSART biology (9–12) test was not available until after we collected our data. However, tests at two levels allowed us to compare SMK needed to teach at the middle school level versus more advanced high school science content.
4. With similar courses we reviewed course descriptions to determine equivalency (e.g., *General Biology I* and *Introduction to Life Science I*).
5. Due to space constraints we refer readers to conference presentations (Lewis, et al., 2018) and an article (under review) that provides greater detail on these analyses.
6. Since the writing of this chapter we completed a new analysis of physics minimum credit hours and included teacher candidates' mathematics coursework and GPA. This work is currently in preparation.
7. Other independent variables that were removed from the model were science credit hours (total and by subject) and GPA by subject since they did not have a significant effect on inquiry-based instruction in physical science lessons.
8. Since the writing of this chapter our new analyses, Lewis et al. (under review) suggest that mathematics coursework and mathematics GPA is also important to include in determining minimum amount of coursework and mastery levels.
9. Once sufficiently powered we will be analyzing teacher candidates' and undergraduate life sciences majors' performance on the new MOSART biology (9–12) test and investigate the relationship between middle school and high school content mastery.

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