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Effects of subject-area degree and classroom experience on new chemistry teachers' subject matter knowledge

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ABSTRACT

Science teachers need to understand the subject matter they teach. While subject matter knowledge (SMK) can improve with classroom teaching experience, it is problematic that many secondary science teachers leave the profession before garnering extensive classroom experience. Furthermore, many new science teachers are assigned to teach science subjects for which they do not hold a degree. This study investigates the SMK of new secondary science teachers assigned to teach chemistry in their first three years of teaching. These new teachers do not have the advantage of years of experience to develop their SMK and half hold a degree in biology rather than chemistry. This qualitative study explores the effects of holding a degree in the subject area one teaches as well as classroom teaching experience on teachers' SMK for two chemistry topics, conservation of mass and chemical equilibrium. Qualitative analysis of semi-structured interviews indicated that the SMK of teachers who had a chemistry degree and more extensive classroom experience was more coherent, chemistry-focused, and sophisticated than that of teachers who lacked this preparation and experience. This study provides evidence that new science teachers' SMK is influenced by both holding a degree in the subject area and having classroom experience.

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Science teachers need to understand the subject matter they teach (Abell, 2007; van Driel, Berry, & Meirink, 2014), including knowledge of the concepts of their discipline and concepts that cut across the different disciplines (National Research Council [NRC], 2012). In addition, they need to understand the processes and practices associated with their discipline. These dimensions of subject matter knowledge (SMK) are the basis for many of the instructional decisions that will be made in a science classroom (Gess-Newsome, 1999).

Studies have shown that the SMK of secondary science teachers improves as they interact with the curriculum and engage in professional development programs (e.g. Arzi & White, 2008; Diamond, Maerten-Rivera, Rohrer, & Lee, 2014). Although SMK can

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improve over time, it is of concern that new secondary science teachers comprise a large portion of the teaching population (Ingersoll, Merrill, & Stuckey, 2014). Furthermore, many new science teachers are assigned to teach science subjects for which they have not been prepared (Banilower, Trygstad, & Smith, 2015).

This study is focused on new secondary science teachers assigned to teach chemistry in their first three years of teaching. These new teachers do not have the advantage of years of experience to develop their SMK and half of them hold a degree in biology rather than chemistry, yet they need to teach at the level of their experienced peers. This qualitative study explores the effects of holding a degree in the subject area one teaches and of classroom experience on teachers' SMK for two chemistry topics; conservation of mass and chemical equilibrium. The specific question guiding this study is: How do degree and classroom experience of new chemistry teachers affect teachers' SMK of conservation of mass and chemical equilibrium? Through analyzing their explanations, we make inferences about their SMK for these two topics.

Theoretical Framework

A guiding assumption of this study is that teacher knowledge is significant because it influences classroom instruction and student learning (Abell, 2007; Diamond et al., 2014; Grossman, Wilson, & Shulman, 1989; National Research Council [NRC], 2007; Sadler, Sonnert, Coyle, Cook-Smith, & Miller, 2013). Our conceptualization of teacher knowledge fits into the tradition prominently begun by Shulman (1986), which identifies distinguishable interacting knowledge bases. Many models in this tradition focus on pedagogical content knowledge (PCK), a form of professional knowledge that enables teachers to make subject matter comprehensible for students (Abell, 2007; van Driel et al., 2014).

Teachers must understand subject matter if they are to make it comprehensible for students (Abell, 2007; McConnell, Parker, & Eberhardt, 2013). While this understanding must be transformed or integrated with other knowledge bases to develop PCK (Gess-Newsome & Lederman, 1999), SMK is distinguishable from PCK (Baumert et al., 2010; Jin, Shin, Johnson, Kim, & Anderson, 2015). This study focuses on three domains of teacher SMK (Luft, Hill, Nixon, Campbell, & Dubois, 2015). *Core content knowledge* consists of the fundamental concepts of the scientific discipline the teacher is responsible for teaching. *Specialized content knowledge* comprises the scientific knowledge required to accomplish a teachers' work, including the scientific understanding required to make sense of student responses. *Linked content knowledge* includes the connections that relate scientific concepts. These domains are similar to those found in the mathematical knowledge for teaching model (Ball, Thames, & Phelps, 2008), which is just beginning to be applied in science education (e.g. Johnson & Cotterman, 2015).

This study draws upon the explanations provided by teachers about chemistry phenomena in order to determine the quality of their SMK. Being able to provide explanations is seen as a core aspect of scientific proficiency (NRC, 2007). Past studies have used explanations to assess the conceptual understanding of students (e.g. Ford & Wargo, 2012; Oversby, 2002) and teachers (e.g. Quilez, 2004).

Related Literature

Subject matter knowledge

Studies have provided evidence that SMK is a foundational component of PCK and important for teaching. For example, Rollnick et al. (2008) found that three South African teachers' SMK influenced their methods of representing the subject matter to students, their design of assessment tasks, and their choice of instructional strategies. In the model that emerged from their findings, SMK was found to be one of the 'four fundamental domains of knowledge for teaching' (p. 1380). In another study, Chan and Yung (2015) investigated the development of PCK, specifically instructional representations, during classroom instruction. For some teachers, SMK facilitated the development of new representations; for others, inadequate SMK inhibited this development.

SMK is also known to influence classroom practice (Abell, 2007; Davis, Petish, & Smithey, 2006; van Driel et al., 2014; Gess-Newsome & Lederman, 1995; NRC, 2007). Sanders, Borko, and Lockard (1993), for example, investigated experienced science teachers' instruction as they taught in their area of certification and experience and as they taught in a new subject area for which they were not certified and had taught less than twice. They found that teachers acted like novices in many ways when teaching a new subject area. For instance, teachers struggled to respond to student questions about the science content and relied more on closed instructional strategies such as lecture or seatwork compared to their instruction in their specialty subject.

Degree in the subject area

Holding a degree in the subject area one teaches is generally considered an important aspect of developing teachers' SMK. This expectation is apparent in the requirement that a teacher hold a degree (or equivalent coursework) in the subject area to be considered 'highly qualified' (U.S. Department of Education, 2002). Additionally, researchers have used a degree as a proxy for teacher SMK (Abell, 2007). Monk (1994), for instance, found that the number of courses science teachers had taken in their field was positively related to student scores on a science test. Other studies, however, found that students of teachers with science degrees performed no better than students of teachers without science degrees (Diamond, Maerten-Rivera, Rohrer, & Lee, 2013; Goldhaber & Brewer, 2000). Because of contradictory results, scholars have argued for the importance of direct measures of teacher SMK rather than relying on a degree as an indication of SMK (e.g. NRC, 2007; Wilson, Floden, & Ferrini-Mundy, 2001).

The primary finding of studies that have used direct measures of teachers' SMK is that science teachers overall have inadequate SMK. Many researchers have found that teachers hold misconceptions similar to those observed in students (Abell, 2007; Haidar, 1997; Kind, 2014). One such study conducted in Spain explored prospective and practicing teachers' explanations of chemical equilibrium changes in gaseous systems (Quilez, 2004). Few correct explanations were provided, with many teachers incorrectly drawing on Le Chatelier's Principle. Other studies have posited that teacher SMK is incoherent and disjointed. Haidar (1997), for instance, found that prospective teachers at the junior and senior levels in Yemen had fragmented and incorrect knowledge for conservation of mass and related concepts. He concluded that it was poor content instruction at the university level that led to these misconceptions.

A few studies have linked direct measures of teacher SMK with university coursework. In a study of successful Swaziland teachers, Mthethwa-Kunene, Onwu, and de Villiers (2015) found evidence that these teachers held correct declarative, procedural, and conditional SMK (knowing what, how, and why, respectively) related to genetics. The teachers attributed this knowledge to their university content coursework. Großschedl et al. (2015) also connected a direct measure of SMK with college coursework, finding that German prospective biology teachers who completed additional biology courses scored better on SMK measures than teachers who had finished less biology courses. These researchers attributed the differences in SMK to increased opportunities to learn the content afforded by additional content coursework. This connection between coursework and SMK, while largely assumed, is just beginning to be investigated. In this study, we are interested in the affect of a degree in the subject area because earning a degree in a subject area requires extensive subject-specific coursework.

The connection between coursework and teacher SMK should be investigated because the scientific knowledge intended to be taught in university coursework is different than the scientific knowledge needed for teaching. First, topics included in content coursework do not necessarily align with topics included in the K-12 curriculum (NRC, 2007). The topics that are most important for a college physics course, for example, differ from the topics that are most important in a high school physics course (Deng, 2001). Second, scholars have argued that teachers need to understand the subject matter in unique ways, specialized for the distinctive work of teaching (Bullough, 2008; Deng, 2007; Dewey, 1976). As university content coursework is not focused on developing the unique SMK needed for teaching, it is important to investigate how such coursework contributes to the development of teachers' SMK.

Classroom experience

Classroom experience as a teacher has long been seen as important in the development of multiple forms of teacher knowledge. Many teacher educators believe that classroom experience allows prospective teachers to 'test the knowledge they have acquired … in the crucible of the classroom' (Grossman, 1990, p. 15). This conjecture has some weight. In their handbook chapter on teacher knowledge, Cochran and Jones (1998) reported that classroom experience improved prospective science teachers' knowledge. Other reviews on the knowledge of science teachers have made similar assertions (Abell, 2007; van Driel, Verloop, & de Vos, 1998; van Driel et al., 2014). These conclusions have been used to argue for increased classroom experience during teacher preparation (Cochran & Jones, 1998).

There is evidence that classroom experience leads to the development of science teachers' PCK. For example, in a German study of prospective biology teachers, participants with greater teaching experience (a maximum of 10 lessons previously taught) obtained higher PCK scores than those without teaching experience (Großschedl, Harms, Kleickmann, & Glowinski, 2015). Another study found that new science teachers' PCK in the area of understanding student learning improved significantly over their first year of teaching (Lee, Brown, Luft, & Roehrig, 2007). Chan and Yung (2015) explored how experienced teachers developed their PCK while teaching. These teachers developed new instructional representations (an aspect of PCK) as they encountered unexpected student responses, unanticipated student questions, or other stimuli in the classroom; this result demonstrates the important role of experience in PCK development.

Classroom experience has been shown to influence additional forms of teacher knowledge. One study compared the knowledge of participants with and without classroom experience in an alternative certification program (Friedrichsen et al., 2009), concluding that participants with classroom experience had more integrated pedagogical knowledge than those without classroom experience, although they did not have notably different PCK. Lederman, Gess-Newsome, and Latz (1994) found that as prospective biology teachers planned and enacted lessons, their pedagogical knowledge and SMK became more coherent. Similarly, as Hauslein, Good, and Cummins (1992) compared the knowledge of prospective biology teachers, new biology teachers, experienced biology teachers, biology graduate students, and biologists, they found that experienced teachers' biology SMK, like that of biologists, was highly structured and organized. Additionally, as Arzi and White (2008) followed 22 Australian secondary science teachers over 17 years, documenting their SMK using concept maps, they found that these teachers' SMK became more comprehensive and coherent for topics they regularly taught.

While these studies provided some information on the development of teacher knowledge with classroom experience, our understanding is still limited in two areas. First, because studies on teacher knowledge development focus primarily on development during teacher preparation (e.g. Lederman et al., 1994) or over many years of experience (e.g. Arzi & White, 2008), little is known about teacher knowledge development during the early years in the classroom. While the first three years of a teacher's career generally include significant improvements in effectiveness (Henry, Fortner, & Bastian, 2012), they are filled with many unique challenges (Davis et al., 2006; Luft, Dubois, Nixon, & Campbell, 2015). Understanding how teachers develop during this phase is necessary for providing them with better support. Because of the high turnover within the first five years (Ingersoll et al., 2014), waiting for teachers to improve over many years of classroom experience is unrealistic.

Second, there is limited research on the influence of classroom experience on teachers' SMK (van Driel et al., 2014; Leeferink, Koopman, Beijaard, & Ketelaar, 2015). In their review of research on science teacher knowledge, van Driel et al. (2014) stated, 'There still have been relatively few studies on the development of SMK in the context of teaching' (p. 854). Studies on the influence of classroom experience on teacher knowledge tend to focus on PCK or pedagogical knowledge, leaving SMK largely unexplored.

Methods

An exploratory qualitative design was used to investigate the effects of a subject-area degree and classroom experience on new chemistry teachers' SMK. Participants who held a degree in biology were contrasted with participants who held a degree in chemistry. Teachers' explanations of chemistry concepts provided insights into their SMK. As SMK research is just emerging, an exploratory design was well suited for this study.

Participants

Participants for this study were a cross-sectional sample of six new teachers who had been teaching chemistry as their primary subject during their brief careers (see Table 1). Two of these teachers were in their first year of teaching, two were in their second year, and two were in their third year. In each experience category, one teacher had earned a degree in chemistry (or equivalent coursework), and one teacher held a degree in biology. Pseudonyms are used throughout the study, with accompanying abbreviations designating years of experience (e.g. Y1 for first year) and degree area (i.e. *B* for biology and *C* for chemistry). All teachers taught in the same southeastern state in the U.S. The participants were part of a larger study on teacher knowledge, who had been recruited through recommendations from teacher educators and school administrators. All of the participants received small stipends for being part of the study.

Data sources and collection

Data for this study came from semi-structured interviews probing teachers' SMK for the topics of conservation of mass and chemical equilibrium. These significant topics in chemistry (Ganaras, Dumon, & Larcher, 2008; Özmen & Ayas, 2003) are important in the curricula of many countries (NRC, 2012; Sahin Pekmez, 2010) and a number of studies have found that students and teachers struggle with these topics (e.g. Ganaras et al., 2008; Kaya, 2013; Özmen & Ayas, 2003; Quilez, 2004). Participants responded to a set of questions on both topics.

Each interview set began by asking the new teacher to describe either how mass is conserved in a chemical reaction or to describe how a chemical reaction reaches equilibrium (intended to elicit *core content knowledge)*. The new teacher was then presented with a classroom scenario in which students expressed an error in scientific understanding. The conservation of mass scenario involved a classroom demonstration in which the teacher burned a piece of paper on a scale. When the reading on the scale went down, students explained that it did so because the paper turned into flame. In the chemical equilibrium scenario students expressed the idea that no changes occur when a system is at chemical equilibrium. The remaining questions referred to the classroom scenario. The teacher was asked to explain what was difficult about the topic for students and to identify topics that could precede and follow the topic in the scenario. These last questions corresponded with the domains of *specialized content knowledge* and *linked content knowledge*.

Data were collected by a team of four research assistants (all doctoral students at the time, including the first author) and a faculty member (the third author), who was the principal investigator for the larger study. Prior to interviewing the participating teachers,

Table 1. Participants' degree and experience.

Participant	Degree	Year of teaching
Aaron	Biology	1
Addie	Chemistry	1
Marisa	Biology	2
Aubrey	Chemistry	2
Heidi	Biology	3
Madison	Chemistry	3

the team reviewed the question format and practiced the interviewing technique. In addition, different members of the team were assigned to interview different new teachers (Miles, Huberman, & Saldaña, 2014). This process of training and assigning different interviewers contributes to the validity of the interview process as a form of researcher triangulation (Miles et al., 2014; Seidman, 2013).

The digitally recorded interviews lasted approximately 20 minutes. As the new teachers responded to questions about conservation of mass and chemical equilibrium, interviewers asked clarifying questions following guidelines found in Seidman (2013). Follow-up questions were included to probe the depth of the teachers' knowledge: Can you tell me more about this answer? What do you mean by ___? Can you tell me about a specific example? Thus the interviewers sought to understand things that were unclear and to explore the teachers' explanations. The semi-structured nature of the interview also allowed for adjustments to be made to participant responses while maintaining a level of consistency across interviews (Bogdan & Biklen, 2006; Kirk & Miller, 1986). Upon completion, each interview was downloaded to a secure location and transcribed.

Data analysis

Transcribed interviews were imported into NVivo 9 (QSR International, 2010), a qualitative analysis program. First, two researchers (the first and second authors, who were both doctoral students at the time) collaboratively constructed a profile for each participant through multiple readings of the data in order to identify patterns in the teachers' explanations (Miles et al., 2014). Each profile included three to four paragraphs describing the participant's explanations. Researchers examined the profiles and identified features that were salient across all of them (Miles et al., 2014; Saldaña, 2013). To do this, researchers first worked independently to generate a list of salient features, then came together, compared their lists, and agreed on the selected features, which included: overall response correctness (scientific accuracy), chemistry focus (depth of chemistry-specific knowledge demonstrated), and connections and structure (coherence of responses and relationship of concepts).

Researchers then explored the construct table to identify patterns in teachers' explanations. They noted that within each of the features the explanations progressed from simple to complex in three levels. The three levels of the feature of *overall response quality* were (a) inaccurate in some ideas and/or connections, (b) mostly accurate, containing only minor errors or unclear statements, and (c) scientifically accurate and precise. For the feature of *chemistry focus*, the levels for responses were (a) responses that did not identify major concepts and/or drew on ideas from outside the discipline of chemistry, (b) responses that discussed only chemistry ideas, leaving off some important chemistry concepts, and (c) responses that identified important chemistry concepts not mentioned in the prompt (e.g. reactants and products, reaction rates). Finally, levels for the *connections and structure* feature included (a) responses that either made no connections or made inappropriate connections, (b) responses that only superficially connected concepts, and (c) responses that connected concepts with a big idea. The level into which each explanation fit was identified on the construct table by coloring each cell, with darker colors indicating that the response belonged to a more complex level.

This color coding allowed researchers to explore variations related to classroom experience and degree.

Furthermore, researchers noticed differences in the quality of explanations teachers provided. In order to distinguish levels of quality of these new teachers' explanations, researchers drew on Oversby's (2002) *ladder of explanations*. This ladder is a framework for distinguishing levels of conceptual understanding in chemistry (see Table 2).

Oversby's (2002) ladder of explanations includes five levels of sophistication. At the *definitional* level, explanations identify the phenomenon, defining it but not providing details about what is occurring. *Descriptive* level explanations move beyond merely identifying and provide observations regarding the phenomenon. Both definitional and descriptive explanations center on tangible and visible objects and phenomena, known as the macro level (Johnstone, 1991). Moving into the *interpretative* level, an explanation must utilize theoretical entities to describe the phenomenon. For example, rather than stating that the mass before and after a chemical reaction must be equal, an interpretative explanation refers to the number of atoms before the reaction equaling the number of atoms after. *Causal* explanations identify the mechanism for the phenomenon, which often requires reference to atoms and molecules. Thus interpretative and causal explanations refer to substances and phenomena happening at very small scales (e.g. molecules, ions), known as the submicro level (Johnstone, 1991). The most sophisticated level of explanation, *predictive*, provides a generalizable principle that allows one to predict future phenomena or to predict the same phenomenon in other circumstances.

Throughout this analysis, validity was strengthened in two primary ways. First, multiple researchers worked both separately and together to engage multiple viewpoints (Miles et al., 2014). Because one researcher was familiar with the data and participants prior to analysis and the other was new to the data, one was able to provide contextual background and the other to provide spontaneous insights. Second, when the construct table was completed, the researchers returned to the data to seek alternative explanations (Merriam, 2009). This involved reviewing the transcripts for evidence that would contradict the current salient features or suggest additional salient features to be considered.

Table 2. Ladder of explanations for chemistry.

Level of explanation	Description	Example for conservation of mass	Example for chemical equilibrium
Definitional	Identification of phenomenon	Matter cannot be created or destroyed	Equilibrium is a balance
Descriptive	Describe phenomenon	Mass before a reaction is equal to the mass after a reaction	There is no observable change when a system is at equilibrium
Interpretative	Refer to theoretical entities	Number of atoms before a reaction are equal to the number of atoms after	At equilibrium, bonds are being broken and formed
Causal	Identify mechanism	Atoms are rearranged in a reaction and do not cease to exist	The rate of the forward and reverse reactions are equal at equilibrium
Predictive	Generalize to predict other phenomena or the phenomenon in other circumstances	As atoms are rearranged in a reaction, they can create substances that are not easily detectable	Because the forward and reverse reactions are occurring at the same rate at equilibrium, no change is observed

Limitations

A few limitations of this study should be acknowledged. The sample of teachers was small, and the number of topics was limited. Research including more teachers and additional topics might produce different findings. However, our interview process provided us with an adequate understanding of participants' knowledge of these two chemistry topics – which was a form of data saturation (Creswell, 2008). Furthermore, the findings of this study rely on the assumption that each participant's knowledge is represented by what was said during interviews and how it was said. However, efforts were made to insure confidentiality and establish rapport in order to enhance the quality of the interview data (Seidman, 2013).

We also acknowledge that additional factors, such as participation in professional development activities, could contribute to teachers' SMK. However, only one teacher reported participating in a meaningful chemistry-specific professional development activity. All teachers reported planning collaboratively with colleagues but lacking other chemistry-specific supports at the school and district levels. While not fully accounting for the effects of all possible factors, this report suggests that these factors did not contribute to patterns observed in these data. Although the findings from this exploratory qualitative study have limitations, they do provide insights into the nature of new chemistry teachers' SMK.

Findings

The presented findings describe insights into ways teachers' explanations varied related to years of classroom experience and whether or not they held a chemistry degree (see Table 3). Each of the following findings arose from analysis of one of the features identified above. The first finding is related to the feature of *overall response quality* as coherence is an aspect of

Table 3. Levels of participants' explanations for each feature.

	Aaron (Y1B)		Marisa (Y2B)		Heidi (Y3B)		Addie (Y1C)		Aubrey (Y2C)		Madison (Y3C)	
	1	2	1	2	1	2	1	2	1	2	1	2
Overall response quality												
Chemistry focus												
Connections and structure												
Sophistication												

Note: Each column represents a participant's explanation for either interview set 1 (conservation of mass) or interview set 2 (chemical equilibrium). Cell color indicates the quality of the explanation for that feature. Darker cells identify more complex explanations. There are three levels for the first three features and five levels for the last feature.

overall response quality that varied with experience and degree. Findings 2 and 3 were drawn from analysis of the *chemistry focus* and *sophistication* features, respectively. Finally, Finding 4 is a result of the *connections and structure* feature as this feature involved the sequencing of topics. Each of these themes is an aspect of SMK.

Finding 1: teachers with a chemistry degree and more classroom experience provided more coherent explanations

Aubrey (Y2C) and Madison (Y3C) gave explanations that were distinctly more coherent and structured than those of the other teachers. Both of them hold a degree in chemistry and have completed their first year of teaching. A representative segment was Aubrey's (Y2C) description of the combustion reaction as she explained how she would help students understand that mass had been conserved:

> We will start with writing a chemical reaction (what the paper is made of) and then what is happening while the paper is burning … And then we will talk about the flame … that is energy that is being released [as] visible light … And then we will talk about the physical state of the … products. For example … water, we say, 'Okay, but water is liquid, why we don't see it?' Then we'll talk about the high temperature from the released heat and water vaporizes. (pp. 359–372)

In this explanation the ideas are well ordered and coherent. It is easy to follow Aubrey's progression from identifying reactants then products to identifying the challenge with observing the product of water. This type of structure is apparent throughout Aubrey's and Madison's responses.

Aubrey and Madison also showed their ability to structure their thinking and expression by their style of responding directly, correctly, and concisely. For example, Madison (Y3C) explained the conservation of mass: 'The total mass of the reactants must equal the total mass of the products. The total mass before the reaction must equal the total mass after the reaction' (pp. 569–570).

Such a direct and concise answer is a stark contrast to responses from the other teachers. For example, contrast Aaron's (Y1B) explanation of why students made an error described in the scenario.

> They're not understanding that heat is actually something that we measure. We don't measure the flame. A flame doesn't weigh; we're not measuring a flame. They're not considering all the different chemical states of a substance. It can be gas, it can be physical, it can be liquid – they're not thinking about all the states of matter. That's what it seems like. You can always weigh matter. (pp. 33–37)

Here Aaron moved between ideas of heat, flame, states of matter, and weight, which suggests that these concepts are not well structured within his knowledge base. While the explanations of Aubrey and Madison are easy to follow, it is challenging to follow the logic through many of the other teachers' explanations.

Finding 2: teachers with a chemistry degree and more classroom experience provided more chemistry-focused explanations

In explaining the conservation of mass and chemical equilibrium, Aubrey (Y2C) and Madison (Y3C) drew on detailed chemistry knowledge. For example, when discussing chemical equilibrium Madison identified the key concept of reaction rates and cited the advanced concept of energetic favorability: 'When [does the reaction] reach [equilibrium]? When it is no longer energetically favorable to continue going in one direction or another' (pp. 625–626). While considering a potential teaching strategy for chemical equilibrium, her discussion of radiolabeling products and reactants demonstrated a complex understanding of advanced chemistry concepts. Aubrey's (Y2C) detailed chemistry knowledge was evident in her discussion of acetic acid dissociating in water to explain chemical equilibrium. She said, 'When dissolved in water [acetic acid starts] to ionize and [an] acetate ion is formed. And a hydrogen ion is formed, which we know it is not exactly [a] hydrogen ion, it is attached to a water molecule' (pp. 485–487). She went on to describe the process of the forward and reverse reaction rates reaching equilibrium. Throughout their responses, neither Aubrey nor Madison drew on concepts outside of the discipline of chemistry.

On the other hand, Aaron (Y1B), Addie (Y1C), Marisa (Y2B), and Heidi (Y3B) did not identify important or advanced chemistry concepts, but rather supported many of their explanations with concepts from disciplines outside of chemistry. Also a difference was observed between the knowledge drawn on by more experienced teachers Marisa (Y2B) and Heidi (Y3B) and by first year teachers Aaron (Y1B) and Addie (Y1C). Marisa and Heidi referred to concepts from biology. For instance, when Heidi (Y3B) explained chemical equilibrium she drew primarily on the concept of the dynamic balance of population size and genetic equilibrium. She stated that she thought of equilibrium as similar to a situation 'where the population isn't growing and it isn't shrinking because of predators or natural selection, it's just at a fixed rate because births and deaths are equal' (pp. 549–555). This is a good approximation of chemical equilibrium, and while just an approximation, it seems to be a productive way to buttress her chemistry knowledge.

Aaron (Y1B) and Addie (Y1C), on the other hand, drew on concepts outside of either chemistry or biology to explain these chemistry topics. To illustrate, Aaron (Y1B) identified the concept of the water cycle as a real world example to help students understand chemical equilibrium. He stated, 'So, water's liquid. Say we're boiling it off, it's actually vaporizing right? … So if it condenses, like up in the clouds … then it's going to come back down as liquid again' (pp. 1–4). Though it seems clear that Aaron was referring to the reversibility of change demonstrated by the water cycle, which is inherent in chemical equilibrium, this seems like a distant connection. Addie (Y1C) also went outside chemistry as she indicated that the cause of students' error about chemical equilibrium comes from the use of the word in other disciplines. Equilibrium, she said, is the 'type of word [that] also shows up in literature or history. [These fields] say that things were in a "state of equilibrium," so from our content it just means something a little different' (pp. 291–294). These concepts do not appear to productively support Aaron and Addie's explanations of chemistry concepts.

Finding 3: teachers with a chemistry degree and more classroom experience provided more sophisticated explanations

Oversby's (2002) ladder of explanations was used to distinguish the sophistication of teachers' explanations. Aubrey (Y2C), Heidi (Y3B), and Madison (Y3C) provided explanations at a higher level than did Aaron (Y1B), Addie (Y1C), and Marisa (Y2B).

Explanations by Aubrey, Heidi, and Madison were at the interpretative level or higher, but explanations by Aaron, Addie, and Marisa were at the interpretative level or lower. The teachers who supplied higher-level explanations were either in their third year (Heidi and Madison) or second year with a chemistry degree (Aubrey). Teachers who provided lower-level explanations were either in their first year (Aaron and Addie) or second year with a biology degree (Marisa).

Definitional explanations include Addie's (Y1C) definition of chemical equilibrium, which focused on equilibrium as a balance: 'It goes to equilibrium by kind of balancing out between the two – the reactants and the products' (pp. 243–244). Her focus on balance did not identify any macro (e.g. change of color) or submicro (e.g. atoms) properties of equilibrium.

This sample of teachers also provided explanations at the descriptive level. For instance, Aaron (Y1B) stated,

> You start off with 10 grams of A and 10 grams of B – reactant A, reactant B – you're going to end up with 20 grams of product. It might be in a different form, but it's going to be 20 grams of whatever you have. (pp. 4–6)

Aaron's (Y1B) and Marisa's (Y2B) responses were also at this level, focusing on the idea that mass does not change during a chemical reaction.

Teachers in both groups provided interpretative explanations. Addie's (Y1C) explanation of the conservation of mass relied on the idea that 'the molar quantities [in a reaction] have to stay the same' (pp. 188–189). Heidi's (Y3B) explanation of chemical equilibrium referred to the theoretical entities of chemical bonds: 'Bonds will be broken and come back together' (p. 521). Though both of these teachers identified the role of theoretical entities (molar quantities, chemical bonds) in the phenomenon, they did not refer to the mechanism that caused equilibrium (i.e. rates of the forward and reverse reactions being equal).

Teachers with chemistry degrees who had already completed their first year of teaching provided predictive level explanations, the most sophisticated level. Both Aubrey (Y2C) and Madison (Y3C) connected the submicro mechanism with the macro phenomenon while considering student errors. Madison explained that, at equilibrium, the forward and reverse reactions are 'just happening at the same rate so you can't tell from the outside that anything's going on' (pp. 642–643). Similarly, Aubrey (Y2C) explained, 'the actual concentration of [the products and reactants] does not change because both reactions are happening with the same rate' (pp. 408–411).

Finding 4: regardless of degree or experience, teachers did not use SMK to determine sequence

When teachers were asked which topics should be taught before and which topics should go after conservation of mass or chemical equilibrium, all teachers spoke about the sequence of their curriculum. Some of the teachers simply talked about the order in which they taught. 'It's something we teach toward the beginning of the semester,' said Heidi (Y3B, 482). Other teachers, including Aaron, referred directly to the state curriculum: 'I honestly don't know the next stage of how I would use this is; I'd just look at what the [state curriculum] says,' (pp. 141–143). The remaining teachers simply provided lists of related topics that came before or after; for example, Aubrey (Y2C) stated that chemical reactions, ions, and bonding came before but gave no justification or logic.

These teachers apparently did not think deeply about the sequencing of the topics based on the logical connections between concepts; they seemed to base their sequencing solely on precedence or mandate. Heidi (Y3B) provided an example when she asked if the interviewer wanted her to explain what she actually taught next or what she thought should be taught next. When the interviewer clarified that she meant the latter, Heidi responded, 'I don't know why I asked you because I don't really have much of an opinion. After it we teach heat and energy and then gas law' (pp. 561–562). In sum, none of these teachers engaged with the content to determine sequence and, instead, relied on the curriculum.

Discussion

This study sought to understand new chemistry teachers' SMK by analyzing their explanations of two chemical phenomena. Results indicated that the SMK of teachers who had a chemistry degree and more teaching experience was more coherent, chemistry-focused, and sophisticated. These results agree with previous studies finding classroom experience influences teachers' SMK (e.g. Arzi & White, 2008; Hauslein et al., 1992).

One aspect showing differences was coherence, which is related to the connections among concepts. This study demonstrated that new teachers can hold coherent knowledge, although previous research had shown the incoherent nature of SMK among prospective teachers (Gess-Newsome & Lederman, 1995). Teachers who hold a degree in the subject area they teach can develop coherent SMK early in their careers. Future research should investigate factors that support development of this aspect of knowledge among new science teachers.

A second aspect emerging from the interview data was the chemistry focus of teachers' SMK. Being able to draw richly from the discipline one is teaching is important (Rollnick, Bennett, Rhemtula, Dharsey, & Ndlovu, 2008); however, some research suggests value in having SMK beyond the specific discipline one is teaching (Nixon & Luft, 2015). SMK that is not chemistry-focused may support a teacher in emphasizing cross-disciplinary connections, including crosscutting concepts (NRC, 2012). Because many teachers are assigned to teach subjects in which they are not academically prepared (Banilower et al., 2015), further research into how knowledge in one discipline may support or constrain teaching in another discipline is warranted.

The sophistication of teachers' explanations was a third aspect of teachers' SMK that was demonstrated in this study. More sophisticated explanations – those that are higher on the ladder of explanations – drew together the macro and submicro levels of chemistry phenomena (Johnstone, 1991). Whereas past research has found that many student difficulties result from connecting these two layers (e.g. Johnstone, 2000), new teachers in this study were able to make this link, which may allow them to present the content in ways that would not be possible otherwise. The ways in which science teachers' SMK affects their presentation of science content is in need of further exploration (van Driel et al., 2014).

Collectively, these three aspects (coherence, chemistry focus, sophistication) comprise *core content knowledge*, a domain of SMK. This study provides evidence that new chemistry teachers' SMK can become coherent, chemistry-focused, and sophisticated during their first three years. While we did not investigate the causes of this development, we speculate on how experience influenced each aspect. First, classroom experience is likely to encourage teachers to reflect on their SMK, an important process for developing coherence (Gess-Newsome & Lederman, 1995). As teachers plan, enact, and reflect on instruction, they tend to create additional SMK connections.

Teachers' SMK may become more chemistry-focused with each cycle of instruction. The processes of planning, teaching, and reflecting help teachers recognize gaps in their chemistry knowledge. Although those gaps may have been skipped over or filled with knowledge from other domains in the earliest teaching experiences, teachers may seek resources to strengthen their chemistry knowledge during future cycles.

The sophistication of teachers' SMK may develop as they are required to provide explanations to students (Chan & Yung, 2015). While prospective teachers have limited opportunities to explain science concepts, new teachers are presented with many opportunities each day. These opportunities may encourage them to draw connections and seek support in developing more sophisticated SMK. As all of these relationships are speculative, future research should investigate factors that encourage and support SMK development through classroom experience.

The findings from this study further point to a deficit in the knowledge of new science teachers. The teachers in this study did not use their SMK to determine sequencing of lessons. The SMK domain that would be most useful for sequencing decisions is *linked content knowledge* (Hanuscin, Lee, Gillstrom, Arnone, & Araujo, 2015; Luft et al., 2015). Rather than use SMK, teachers relied on their knowledge of the curriculum. Past research has similarly indicated that new teachers struggle to link instruction conceptually (Austin, Bloom, Grinnell, & Kirkley, 2011; Gess-Newsome, 1999; Hanuscin et al., 2015; Roth et al., 2011). Ultimately, new teachers may need professional development on constructing conceptually coherent lessons (Roth et al., 2011). Further research investigating the relationship between new teachers' SMK and their ability to sequence lessons conceptually is an important facet of understanding teacher SMK.

The final domain of SMK identified in the theoretical framework, *specialized content knowledge*, was not identified in this analysis. This absence may signal the need for more targeted data and analysis to distinguish this domain of SMK. There are no studies with which we are familiar that have identified instances of specialized content knowledge. If this framework is to be useful, studies need to identify evidence and characteristics of this SMK domain.

This study provides evidence regarding the importance of new teachers having a degree in the subject area they teach. Despite research suggesting that content coursework can lead to misconceptions (e.g. Mthethwa-Kunene et al., 2015), the results of this study indicate that holding a degree in the subject area does provide an important foundation for teachers' SMK. However, a degree alone is not sufficient (Gess-Newsome & Lederman, 1995); teachers need classroom experience as well. Teachers assigned to teach subjects for which they have not been prepared likely need additional assistance as they work to develop their SMK. This support is important because SMK is the foundation for the development of PCK and thus influences their instruction (van Driel et al., 2014). Future research should explore how teachers assigned to teach outside of their specialization deal with challenges of limited SMK and how these efforts influence their instruction.

While teacher preparation programs should do all they can to support the development of SMK, this development needs to continue as teachers enter the classroom. This exploratory study contributes to our limited understanding of the effects of a degree in the science teacher's subject area as well as classroom experience on SMK (van Driel et al., 2014; Leeferink et al., 2015). Moreover, it highlights remaining questions regarding ways to support SMK development.

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