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Metacognition in Undergraduate Chemistry Education: Instructor Perspectives And Students' Use

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METACOGNITION IN UNDERGRADUATE CHEMISTRY EDUCATION: INSTRUCTOR PERSPECTIVES AND STUDENTS' USE

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ABSTRACT

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My dissertation research has been a quest to understand how to improve metacognition development in undergraduate chemistry education. The first step I took in this investigation was to speak with those with the largest influence on an undergraduate chemistry student's education: the instructors. I interviewed seventeen postsecondary chemistry instructors on their thoughts of metacognition, its importance, their current practices for developing their students' metacognition, and their suggestions for how to improve metacognition development in undergraduate chemistry education. After conducting a qualitative reflexive thematic analysis of the interview transcripts, I found that many of these instructors valued metacognition and believed it to be important for their students. Some of these instructors were already implementing metacognition development in their courses and had great suggestions for how to improve metacognition development in undergraduate chemistry education. I also found that some of these instructors had little to no knowledge of metacognition before my interview with them, and that with the many responsibilities they already had as lecturers, tenure-track, or tenured professors they felt overwhelmed by the idea of learning enough about metacognition themselves to be able to teach their students about it. After hearing these instructors' perspectives I concluded that to improve metacognition

development in undergraduate chemistry education, awareness and change needs to happen at a departmental level. I also concluded that activities developed with the intent of implicitly or covertly teaching students about metacognition could benefit students of instructors who do not have the time to gain training in educational psychology. The next step in my dissertation research was to develop an activity that could implicitly engage students' metacognition, which could be easily implemented by those time-strapped instructors. To do this I conducted interviews with twenty-five undergraduate biochemistry students and asked them to solve two buffer problems while thinking aloud. Before they solved the second problem, I asked them questions about how a different student might be led astray in solving the problem. The intent of these questions was to covertly prompt students to think about their own thinking by asking them to think about an "unreflective" or "misguided" student's thought process, and this idea was inspired by another study which asked students similar questions while they responded to a concept inventory. After qualitatively analyzing the transcripts by a codebook thematic analysis process, I found that the questions I asked did prompt students to be more metacognitive, specifically by prompting their metacognitive skills of monitoring and evaluating. From these results I concluded that these questions could be used as a "covert" activity to encourage students' to employ their metacognition, and due to their format they can easily be incorporated into existing activities and assignments.

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CHAPTER I

INTRODUCTION TO METACOGNITION DEVELOPMENT IN UNDERGRADUATE CHEMISTRY EDUCATION

Metacognition is the ability to think about your thinking, which can include an awareness of one's knowledge (metacognitive knowledge) and regulation of that knowledge (metacognitive skills). A student with strong metacognition can regulate their understanding and knowledge. An example of this regulation would be if a student checked their answers and were able to identify any mistakes they made after finishing an exam. In contrast, a student with weak metacognition would struggle to discern what they do not know and to understand why they received a low grade on an exam.

Kruger and Dunning (1999) found that low-scoring students struggle to gauge their understanding and performance ability. They believed that low-scoring students lack metacognitive knowledge, which is why they struggle to know what they know and what they do not know. Knowing what and how to study is an important skill for students and is directly related to metacognition.

Student metacognition has been widely studied in undergraduate general chemistry courses but has not been the focus of many studies in upper-division chemistry courses, such as biochemistry. Metacognition is important for beginning college students in their early courses, and it continues to be important and useful in the upper-level courses as well. Therefore, it was one of my goals to illuminate biochemistry students' metacognitive abilities by conducting semi-structured interviews. In the interviews I asked students to work through questions focused on the concept of buffers. I chose to use buffer questions because buffers are a concept important for many areas of chemistry, and for other disciplines. Buffers are a central topic in biochemistry, so many biochemistry courses require an understanding of buffers. Also, research has shown that buffers are a difficult subject for chemistry students of all levels (Orgill & Sutherland, 2008). This means I could ask questions of my interviewees that were reasonably difficult for them to answer and allowed for a variety of responses.

Another goal in my dissertation research was to understand undergraduate chemistry instructors' perspectives of metacognition, and metacognition development in their classrooms. Despite the large amount of research focusing on students' metacognition, there is scant research focusing on chemistry instructors' thoughts and understanding of students' metacognition. Instructors have a strong influence over what happens in their classroom; they decide what the course goals are, how time in the classroom is spent, what assignments and exams assess of their students, and essentially what information students need to know to earn a passing grade. Since instructors have this large influence over their courses, it is crucial to understand how they perceive metacognition, and to discover any barriers they have experienced in developing their students' metacognition. Many studies on teacher beliefs and instructor perspectives on classroom reform have found that for an instructor to implement change in their teaching, they must be dissatisfied with the status quo (Gess-Newsome et al., 2003; Henderson et al., 2011; Woodbury & Gess-Newsome, 2002). If an instructor does not believe a change in pedagogy to be important and does not believe that their current pedagogy is lacking in some way, they will not change. Thus, to gain insight into undergraduate chemistry teachers' practices concerning the development of their students' metacognition, it was necessary to discern their beliefs about metacognition and its importance (Luft & Roehrig, 2007). To gain this understanding, I interviewed post-secondary chemistry instructors from different undergraduate institutions across Colorado. Thus, I conducted two related studies to better characterize metacognition development in chemistry.

Research Questions

The research questions which guided the chemistry instructor interview study were:

Q1 In what ways do current postsecondary chemistry instructors value their students having metacognitive skills?

Q2 How are current postsecondary chemistry instructors encouraging the development of metacognitive skills in their students?

Q3 What are current postsecondary chemistry instructors' thoughts, suggestions, and strategies for improving metacognition in their students?

Q4 How are these postsecondary chemistry instructors' views on metacognition related to their approaches to teaching, as measured by the Approaches to Teaching Inventory?

The research questions which guided the biochemistry student interview study were:

Q1 How do undergraduate biochemistry students employ metacognitive skills when solving buffer problems?

Q2 How do undergraduate biochemistry students employ metacognitive knowledge when solving buffer problems?

Q3 In what ways does implicitly targeting metacognition change a biochemistry student's metacognitive approach to solving buffer problems?

I completed two related studies from both students' and instructors' perspectives with the purpose of gaining a fuller picture of metacognition development in chemistry education.

CHAPTER II

REVIEW OF THE LITERATURE AND THEORETICAL FRAMEWORKS

Review of the Literature

Introduction

In 1999, Kruger and Dunning established the importance of metacognitive monitoring. They measured students' abilities and their knowledge of their abilities in three areas: humor, logical reasoning, and English grammar. After comparing the students' self-assessed scores with their actual scores on assessments testing these skills, Kruger and Dunning found that the students who were least competent in any one of these areas were least likely to be aware of their incompetence in that area, and most likely to overestimate their ability. Not only did the "incompetent" students misjudge their ability, but the less competent a student was in an area, the larger their overestimation of their ability. Surprisingly, the more "competent" students were also inaccurate in predicting their scores and were likely to underestimate their abilities. This phenomenon has since been known as the Kruger-Dunning effect. From the results of their study, Kruger and Dunning concluded that students who perform poorly in a subject area overestimate their knowledge because they lack the ability to metacognitively monitor their understanding. The "incompetent" students do not have strong declarative knowledge, which would allow them to discern how well they understand something, and they are unable to accurately monitor and self-evaluate their understanding while in the process of learning something new or taking an assessment.

There is evidence of Kruger-Dunning phenomena in the chemistry classroom setting (Bell & Volckmann, 2011; Casselman & Atwood, 2017; Hawker et al., 2016; Mathabathe & Potgieter, 2014; Pazicni & Bauer, 2014). In 2014, Pazicni and Bauer conducted a study of over one thousand general chemistry students, investigating their ability to postdict their percentile ranking on each exam in the course. They observed the Kruger-Dunning effect and established its relevance for chemistry education research. Pazicni and Bauer also found that students' calibrations did not significantly change over time; the students consistently overestimated or underestimated their scores. Hawker et al. (2016), Bell and Volckmann (2011), and Mathabathe and Potgieter (2014) report similar findings in their studies investigating students' ability to predict and postdict their test scores. From these studies, we can conclude that simply asking students to postdict their scores after every exam is not enough to trigger students' metacognitive evaluation or to improve their declarative knowledge. Casselman and Atwood (2017) conducted a similar study to Hawker et al., where they asked students to predict their scores for weekly quizzes in their general chemistry course, but they also provided training with the intent to develop students' metacognitive abilities. Throughout the semester Casselman and Atwood assigned quick exercises for the students to develop their metacognition and improve their declarative knowledge. These exercises required students to develop a study plan for the next quiz, based on their previous quiz score and the feedback provided with the quiz score. After the semester of predicting quiz scores and metacognitive training, Casselman and Atwood observed that the students in the lowest quartile scored 10% higher on the ACS final exam than students in the lowest quartile of the control classroom. Thus, the metacognitive training combined with repeated prediction of quiz scores significantly improved students' scores on their exams, which was due to improvement in their ability to self-evaluate and improve the accuracy of their declarative knowledge. From this study, we can conclude that with training, students can improve their ability to postdict their scores and grow in their declarative knowledge.

From these examples of the Kruger-Dunning effect in chemistry education research, the relevance and importance of metacognition for chemistry students is evident. As will be highlighted below, many science education researchers have investigated metacognition in undergraduate science classrooms and laboratory courses, by studying students' metacognitive abilities, developing methods to measure and characterize students' metacognition, and by developing activities to encourage students' metacognition.

Studies of Students' Metacognition

Many studies researching metacognition in science education have focused on students' metacognition. In their studies, Stanton et al. (2015, 2019), and Dye and Stanton (2017) studied the metacognitive skills employed by introductory-level biology students and upper-division biology students to prepare for their exams throughout their semester-long courses. Stanton et al. (2015) found that even though 98% of the introductory biology students in the study wanted to change their studying strategies, only 45% actually did so. When the researchers asked the other 53% why they did not follow through with their new plans, many said they did not know how. The researchers concluded that while some students only need prompting to engage their metacognition, many students require instruction on how to do so. In their later study of upper-level students, Dye and Stanton (2017) observed that all but one of the fourteen upper-division biology students interviewed were able to use their metacognitive skills in preparation for exams. Many students discussed how they were not required to use metacognition until college, and that they developed their metacognitive skills because of some of the more challenging courses required of science majors. In their 2019 study, Stanton et al. compared how introductory and upper-level biology students evaluated their study plans and strategies. They found that the senior-level students were more likely to employ strategies with the goal of monitoring their understanding, whereas the introductory students were less likely to value such strategies. They also observed that introductory students were not as skilled in evaluating their implementation of study strategies and were likely to discontinue a strategy if they struggled to implement it or if they did not immediately see the benefit. Even though the senior-level students had stronger metacognitive skills in many ways, both groups of students struggled to evaluate the effectiveness of their study plans and strategies, which indicates that students from all levels could benefit from instruction on how to evaluate study strategies.

Rickey and Stacy (2000) found that two novice chemistry students with strong metacognitive skills were more successful in solving non-standard chemistry problems than one graduate chemistry student who was less metacognitive in their problem solving. This study demonstrated that students with strong metacognitive skills can be successful when presented with unfamiliar tasks or problems. González and Paoloni's (2015) model of introductory chemistry students' perceived autonomy support, motivation, metacognition, and achievement in their chemistry course supported the idea that strong metacognitive skills can lead to success for students. González and Paoloni used structural equation modeling (SEM) to understand how introductory chemistry students' perceived autonomy support, motivation, and metacognition were related to each other, and how these factors affected students' achievement in the chemistry course. Their model found positive relationships between metacognition and motivation factors, and metacognition and perceived autonomy support, and found that metacognition predicted students' performance in the course.

Teichert et al. (2017) and Kelly (2014) studied general chemistry students' use of metacognition while learning about molecular representations of different chemistry phenomena. In her study, Kelly (2014) found that students who lacked metacognitive skills struggled to be able to evaluate their own understanding. Students were asked to describe and draw representations of conductive substances before watching a video, which represented conductive substances at the molecular level. After viewing the video, the students were interviewed on their understanding of conductivity, and asked to revise the representations they had made prior to viewing the video. Many students drew pictures in their prior knowledge activity that did not match the video representations, but during the interview the students said that their understanding of conductivity matched what was portrayed in the video. Since these students lacked the ability to see the differences in their drawings and the video representations, Kelly concluded that these students lacked the metacognitive skills necessary to evaluate their own understanding. Teichert et al. (2017) focused on students' understanding of solution processes. In a lab activity, students made explicit their mental models of what was happening at the molecular level when different substances were added to water. Teichert et al. found that students who had accurate metacognitive self-reflection and monitoring of their model development during the lab activity were more likely to have successful learning transfer at the end of the semester.

Methods to Measure and Characterize Metacognition

Multiple methods to measure and characterize metacognition exist, and a few have been developed specifically for chemistry education. The Metacognitive Awareness inventory (MAI) (Schraw & Dennison, 1994) is a widely used inventory for measuring metacognition, which has been employed in a variety of settings and disciplines, including chemistry education. This survey can be used to reliably measure metacognitive knowledge and/or metacognitive skillfulness.

Cooper and Sandi-Urena (2009) developed the Metacognitive Activities Inventory (MCAI) to measure general chemistry students' use of metacognitive skills. Like the MAI, this inventory cannot be used to measure individual metacognitive skills, just overall metacognitive skillfulness. In Cooper and Sandi-Urena's main study and replications, the MCAI had high internal consistency, which meant the students responded consistently and reliably. The evidence of the instrument's validity was significant, even though the correlation values of MCAI score with students' grade point average was low. However, Dianovsky and Wink (2012) demonstrated that if metacognitive development is a part of the course curricula, the MCAI can be validated by measuring the correlation of students' MCAI scores with their course grades.

Lastly, Sinapuelas and Stacy (2015) developed the Learning Approaches Framework for Chemistry to characterize chemistry students' approaches to learning. Sinapuelas and Stacy qualitatively analyzed students' metacognitive skillfulness, and then used this information to describe students' approaches to learning chemistry. Metacognitive skills was one of four criteria analyzed, along with three criteria relating to how students employed different resources to prepare for exams in the course.

Activities to Develop Students' Metacognition

In science education research, a variety of activities have been developed to encourage students to employ and cultivate their metacognition, such as training and instructional activities, curricular changes to support metacognition development, frameworks to promote metacognition, and in-class and out-of-class activities.

Along with the work done by Casselman and Atwood (2017) discussed earlier in this review, there are multiple metacognitive training activities that have been developed and have demonstrated the ability to increase students' achievement in chemistry courses (Cook et al., 2013; Graham et al., 2019; Muteti et al., 2021). Muteti et al. (2021) developed a metacognitive training session which they provided in class in the early weeks of the semester, and from student feedback at the end of the semester they concluded the training had a positive impact on students' study habits. Cook et al. (2013) and Graham et al. (2019) both developed metacognitive training sessions which they implemented outside of class. Cook et al. found their training significantly improved the attendees' exam scores in the course, while Graham et al. found their training increased students' self-efficacy and class scores, with female students experiencing a larger increase in these areas.

Chemistry education researchers have also studied how curricular changes can improve students' metacognition. Mutambuki et al. (2020) found that students in a general chemistry course which included both active learning and metacognitive training aspects achieved significantly higher scores on their final exams compared to students in a course with only active learning, and no metacognitive components. Sandi-Urena's research team (Sandi-Urena, Cooper, Gatlin et al., 2011; Sandi-Urena, Cooper, & Stevens, 2011, 2012) and Kadioglu-Akbulut and Uzuntiryaki-Kondakci (2021) both implemented curricular changes to the laboratory portion of their classes to promote their students' metacognition. Sandi-Urena, Cooper, and Gatlin et al. (2011) and Sandi-Urena, Cooper, and Stevens (2011, 2012) developed a problem-based laboratory curriculum which they found increased students' metacognitive abilities over the course of the semester, and Kadioglu-Akbulut and Uzuntiryaki-Kondakci incorporated journaling activities into their high school chemistry laboratory to develop students' self-regulated learning abilities. When compared to the control class, Kadioglu-Akbulut and Uzuntiryaki-Kondakci found the treatment group of students to be more metacognitive.

Different frameworks or ways of thinking about chemistry have demonstrated the ability to increase students' metacognition. Yuriev et al. (2017) developed the "Goldilocks Help" problem-solving framework, to teach students how to employ metacognitive skills to regulate their learning, and to develop these skills to improve how they approached solving chemistry problems. The MORE (Model-Observe-Reflect-Explain) framework (Tien et al., 1999) was also developed to aid students in solving problems, by giving them a framework to guide them through problem-based laboratory experiments. After studying students' discourse in lab, Tien et al. found that students using the MORE framework were better at monitoring and evaluating their understanding while solving the laboratory problems. The Metacognitive Learning Cycle (MLC) (Blank, 2000) and the process of Triangulation (Thomas, 2017; Thomas & Anderson, 2014) were both developed to aid students in processing new information. In the MLC, students move through four phases of learning when introduced to a new topic or concept: concept introduction, application, assessment, and exploration. Before moving from one phase to the next, they evaluate their understanding. Blank found that students who employed the MLC were more likely to retain knowledge in a delayed posttest. In Triangulation, students process new information or problems by considering the scenario at three different levels of representation: macroscopic, molecular, and symbolic. This framework requires students to think about how they are thinking about a chemistry concept, which encourages students to be metacognitive.

Lastly, many activities for in-class and out-of-class settings have been developed, such as games, online activities, and assignments to increase students' metacognitive reflection. Fishovitz et al. (2020) developed a variant of the "Heads-Up" game, which helped students evaluate their understanding of concepts in biochemistry that were included in the game. Researchers have also developed online and computer-based activities to encourage students' metacognition, such as the OrgChem101 module developed by Visser and Flynn (2018) to improve organic chemistry students' knowledge of reaction mechanisms and their declarative knowledge, and the Hazmat application Sandi-Urena, Cooper, and Stevens (2011) developed and employed to explicitly train students in metacognition. Many have developed assignments and activities that encourage students to reflect and evaluate their understanding in a course (Bowen et al., 2018; Sabel et al., 2017; Swamy & Bartman, 2019; Talanquer, 2017; Ye et al., 2020; Young et al., 2019). Sabel et al. (2017) implemented the use of "enhanced" answer keys, answer keys with reflective questions to prompt students to evaluate their answers to the assignment and to encourage students to become more self-regulated in their learning. Young et al. (2019) had inorganic chemistry students prepare for their exams by using an "exam blueprint" to aid in their discernment of what material they needed to study to be prepared for the exam, which helped students evaluate their understanding and improve their declarative knowledge. Talanquer (2017) employed a concept inventory not only to measure his general chemistry students' knowledge, but also to implicitly stimulate their metacognitive knowledge, by asking the students to think of the answer an "unreflective" student would select. Talanquer found that students who contemplated the "unreflective" student's answer were more likely to choose the correct answer for themselves, when compared against a control group of students who simply completed the concept inventory. The students in the C-D range had the largest difference in scores when comparing the treatment and control group, with the treatment group having higher scores on the concept inventory. Ye et al. (2020) assessed students with concept maps and creative exercises, and compared to control sections without these assessment types, the treatment group of students provided more detailed and sophisticated explanations of course concepts in interviews. Bowen et al. (2018) developed a guided-inquiry lab activity which encouraged students to use their metacognitive skills to build better arguments for the conclusions made from the data they collected via HPLC. Finally, Swamy and Bartman (2019) developed a series of reflective writing prompts for their students to answer throughout the semester, to encourage students to evaluate their understanding of the course material and to discern in which areas they were struggling.

As the reader can observe, there have been many activities developed for undergraduate chemistry students in a variety of courses: general chemistry, organic chemistry, biochemistry, inorganic, and analytical chemistry. Despite these examples of activities that could promote metacognition, these studies did not necessarily measure students' metacognition. In these studies, the idea that the activities promoted metacognition was more of an implication of the research than a research result. Much of the research in CER with the purpose to understand undergraduate chemistry students' metacognition has been limited to introductory and general chemistry courses. Currently, there is very little research focusing on understanding and developing students' metacognition in upper-division chemistry courses, such as organic chemistry or biochemistry. Thus, one goal of my dissertation research was to investigate biochemistry students' metacognition and explore metacognition development for biochemistry students.

Instructors' Views of Metacognition

Another goal of my dissertation research was to understand postsecondary chemistry instructors' views of their students' metacognition. Despite all the research on students' metacognition, there is very little research on post-secondary science instructors' perspectives of metacognition. Beck and Blumer (2016) conducted a survey study which asked laboratory instructors and students a variety of questions about their perceptions of the instruction in laboratory courses, including a few questions about metacognition, but metacognition was not the focus of the survey. Auerbach and Andrews (2018) developed a "Framework of pedagogical knowledge for active-learning instruction in large undergraduate STEM courses" by surveying undergraduate biology instructors on what they thought were effective active learning teaching practices. The instructor participants were provided with three video clips of a large undergraduate biology classroom and asked to identify the effective practices present in the videos, and some of the participants identified "prompting metacognition" as an effective practice. Sandi-Urena, Cooper, and Gatlin (2011) interviewed graduate teaching assistants (GTAs) who participated in their study of a problem-based general chemistry lab course. In the interviews, they discovered GTAs teaching this lab course were challenged in their epistemologies and views of pedagogy, which Sandi-Urena, Cooper, and Gatlin believed was a metacognitive experience for the GTAs. Furthermore, the researchers postulated that teaching a problem-based laboratory course could develop the GTAs' metacognition and improve their ability to think creatively in the research laboratory setting. Adadan (2020) found that pre-service chemistry teachers with higher metacognitive awareness achieved higher scores than the pre-service teachers with low metacognitive awareness after instruction on the topic of gas behaviors. But Adadan did not investigate these pre-service teachers' thoughts on their future students' metacognitive awareness.

There is clearly a lack of research focusing on undergraduate chemistry instructors' perspectives of metacognition. Thus, the second goal of my dissertation research was to fill this knowledge gap by interviewing postsecondary chemistry instructors on their views and understanding of metacognition, and any barriers they have experienced in fostering metacognition in their students.

Theoretical Frameworks

Metacognition Theory

Metacognition was the theoretical and analytical framework for both studies presented in this dissertation and is the theme that ties both studies together. Metacognition is the ability to regulate one's thinking processes and discern the limits of one's cognitive abilities. Metacognition is usually explained as having two main subsets: metacognitive skills and metacognitive knowledge. Metacognitive skills have been described as "regulation of cognition" (Schraw et al., 2006, p.114) and are usually organized into three main components: planning, monitoring, and evaluating (Sandi-Urena, Cooper, & Gatlin, 2011; Schraw et al., 2006). According to some researchers, metacognitive skills also include information management and debugging (Schraw & Dennison, 1994; Zohar & Dori, 2012). When presented with a task, a student may use metacognitive skills to plan how they will complete the task, monitor their progress throughout, and after completing the task evaluate how well they accomplished the goals they set for the task. During the planning stage, the student could use information management to process the information given about the task and apply their knowledge of that information in developing their plan. Debugging is useful when problems arise, either in the monitoring or evaluating phase. A student could use debugging to problem-solve why their plan did not complete the task as they expected it would. The second part of metacognition, metacognitive knowledge, has been characterized as "knowledge of cognition" (Schraw, et al., 2006, p. 114) and is categorized as declarative knowledge, procedural knowledge, or conditional knowledge (Sandi-Urena, Cooper, & Gatlin, 2011; Schraw et al., 2006; Zohar & Dori, 2012). Declarative knowledge is a person's awareness of the limitations of their knowledge. For example, when a student knows that they do not understand a chemistry equation or knows that they know the names of all the elements, they are using their declarative knowledge to discern what they know and what they do not know. Conditional knowledge is the knowledge of when to employ metacognitive or learning strategies, such as when a student knows that flashcards are the best learning strategy for memorization. Lastly, procedural knowledge is knowing how to implement certain learning strategies or procedures, for example, knowing how to make flashcards (Schraw et al., 2006; Zohar & Dori, 2012).

Metacognition was the main theoretical and analytical framework for the student study but was not sufficient for the design and analysis of the instructor study in this dissertation.

Since the instructor study investigated postsecondary undergraduate chemistry instructors' views on metacognition development, it was also necessary to incorporate models of teacher beliefs into the theoretical framework for that study. Below I discuss the models and theories of teacher beliefs that influenced the instructor study.

Models of Teacher Beliefs

Teacher Beliefs "encompass not only thoughts about how teaching and learning occur but also the level of confidence an instructor holds regarding their ability to utilize reformed pedagogies," (Gibbons et al., 2018, p.3). There are many models for teacher beliefs. In their paper, Lund and Stains (2015) discuss a model of faculty instructional decision making, where in the first stage the faculty member is unaware of an evidence-based instructional practice (EBIP), and then in the second stage they are made aware. In the third stage, the faculty member is interested in the EBIP, and learns more to decide if they want to employ the EBIP in their classroom. Many researchers have found that the time between this model's second and third stage is critical—the time right after an instructor becomes aware of a practice and when they are becoming interested. Some would argue that many faculty simply become aware and do not show interest. Studies have shown that if a professor is going to employ a new educational practice, they must hold the belief that there is a need for change, that the status quo of their pedagogy is insufficient in some way (Gess-Newsome et al., 2003; Henderson et al., 2011). As Gess-Newsome et al. (2003) aptly said, "The foundation of systemic change is individual change." (pg. 763)

Another model, the Teacher-Centered Systemic Reform (TCSR) model developed by Woodbury and Gess-Newsome (2002), also emphasizes the importance of teachers' beliefs about teaching with classroom reform. Woodbury and Gess-Newsome developed the TCSR model by synthesizing the current literature on teacher beliefs and educational reform. The three main components they identify as important for enacting educational reform at an institution are the structural and cultural context at the school, the goal of the reform, and the involved teachers' thoughts on educational reform. In a later study, Gess-Newsome et al. (2003) found that even when external barriers (the first two components of their TCSR model, structural and cultural context, and purpose of reform) to change are removed, professors still will only seek to change their pedagogy if they hold the belief that change is necessary and that their current method of teaching is lacking in some way.

Finally, instructor perspectives can also be modeled by understanding their pedagogical content knowledge (PCK). PCK is an instructors' knowledge of how to teach specific content and encompasses many aspects of instructors' knowledge and beliefs about teaching. Most recently, the Consensus model (CM) of PCK (Gess-Newsome, 2015) and the Revised Consensus Model (RCM) of PCK (Carlson & Daehler, 2019) have discussed how instructors' knowledge and beliefs about teaching inform their classroom practices. According to the Consensus model, an instructor's beliefs and orientations towards teaching directly influence which teaching practices are implemented in that instructor's classroom. Similar to Gess-Newsome et al.'s (2003) findings discussed in the previous paragraph, the CM discusses how even though instructors may have knowledge of best teaching practices, they may not choose to implement them if the practices do not align with their beliefs about teaching. The RCM provides more detailed language for discussing the many facets of instructors' PCK. According to the RCM, there are many knowledge bases that can contribute to instructors' PCK: their pedagogical knowledge, knowledge of the content they are teaching, knowledge of students, knowledge of assessment, and curricular knowledge. If researchers were to consider a population of instructors, and attempt to characterize that group's PCK, they would be investigating their collective PCK (cPCK). cPCK could be the knowledge of teaching practices discussed by instructors in the same department, or cultural practices like when a department decides to prioritize using clickers in all their courses. cPCK can have varying grain size as well; all the high school chemistry teachers in Colorado could have some cPCK that differs from the cPCK held by chemistry instructors in a specific school district or at a specific high school in Colorado. What defines cPCK is that it is PCK known to a group of science educators, and therefore is the least personal component of any given instructor's PCK. Personal PCK (pPCK) and enacted PCK (ePCK) are unique to each individual instructor. The cPCK and learning environment for an instructor directly influence their pPCK. pPCK is an amalgamation of an instructor's beliefs and knowledge about teaching and the PCK they have gained from their personal teaching experiences. It is deeply entwined with an instructor's ePCK—the teaching practices they choose to implement in their classroom based on their pPCK. pPCK and ePCK directly interact as described by Alonzo et al. (2019) in the "plan-teach-reflect" cycle. When planning a lesson, the instructor draws on their pPCK. Then when the lesson is implemented, the instructor uses their ePCK to enact the plan they developed with their pPCK. After the lesson, an instructor consciously or unconsciously reflects on the lesson and students' responses to the lesson, and from those reflections will make changes to their pPCK, which will cause them to make adjustments to how they implement that lesson in the future, thus changing their ePCK. According to the RCM (Alonzo et al., 2019) it is challenging for an instructor to distinguish between their own pPCK and ePCK, and thus the best way to investigate an instructor's ePCK is to gain more understanding of their pPCK.

There have been multiple methods developed to measure and discern teacher beliefs, such as self-report inventories (Trigwell et al., 2005; Woolley et al., 2004), interview protocols (Luft & Roehrig, 2007), and observational protocols (Durham et al., 2018; Sawada et al., 2002; Smith et al., 2013). Self-report inventories are the most cost- and time-effective method for collecting data on teacher beliefs. Despite their efficiency, some researchers have found that self-report inventories are not reliable for discerning a consistent understanding of a group of teachers' beliefs over long periods of time (Herrington et al., 2016). Other methods to discern teacher beliefs such as interview or observational protocols, require more time and resources, but provide a deeper understanding of teacher beliefs. For this reason, I chose to employ interview methods to investigate instructor perspectives on metacognition development.

Importance of Teacher Beliefs

As is discussed in the CM and RCM of PCK, an instructor's beliefs and orientations to teaching have a strong influence over what practices they enact in their classrooms. Their beliefs, which are a major component of their pPCK, directly impact their ePCK, what they choose to enact and implement in their classroom settings. Especially in an undergraduate setting, the instructor's beliefs significantly affect what happens in their course: the goals of the course, how the material is presented, and what skills the instructor expects students to learn from the course. As Luft and Roehrig (2007) stated: "Capturing the beliefs of teachers is important to those in science teacher education—ultimately, beliefs reveal how teachers view knowledge and learning, and suggest how they may enact their classroom practice" (p. 47).

After reviewing the current literature on implementing evidence-based teaching practices in STEM, Henderson et al. (2011) concluded that instructors will only seek to change their teaching practices if they are dissatisfied with the current status of their course, and if they are knowledgeable of how to implement changes which will allow them to reach the goals, or standards, they believe their current course is not meeting. Thus, to understand how undergraduate chemistry students may experience metacognition development in their chemistry courses, it was crucial to first investigate how postsecondary chemistry instructors value metacognition, and what they currently do to support their students' metacognition development.

CHAPTER III

METHODOLOGY

Introduction to Methodology: Study Design

The two studies presented in this dissertation employed qualitative research methods to gain a rich understanding of the research questions being studied. Qualitative methods are an excellent way to gain understanding of someone's beliefs on a subject and their thought processes while completing a task. These methods allowed me to gain a deep understanding of the instructors' beliefs of their students' metacognition, metacognition development in their courses, and of the metacognition biochemistry students employed while solving buffer problems. Zohar and Dori's (2012) discussion of metacognition in science education greatly influenced both study designs and data analysis. For a detailed description of this discussion, and the definitions of metacognition, metacognitive knowledge, and metacognitive skills, please refer to chapter 2 of this dissertation, specifically the theoretical framework.

Part A: Instructor Study

Study Purpose and Research Questions

The purpose of the instructor study was to employ qualitative interview techniques to collect data on these chemistry instructors' thoughts on their students' metacognition development, in order to understand these instructors' relevant pPCK and ePCK. As discussed in the theoretical framework in chapter 2, instructors, particularly at the undergraduate level, have a large influence over what their students learn and experience in their courses. Because of this influence, it is crucial to understand the perspectives of undergraduate chemistry instructors regarding their students' metacognition development, to understand what barriers to metacognition development in chemistry education exist and how these chemistry instructors view metacognition development.

The research questions guiding this study are:

Q1 In what ways do current postsecondary chemistry instructors value their students having metacognitive skills and knowledge?

Q2 How are current postsecondary chemistry instructors encouraging the development of metacognitive skills and knowledge in their students?

Q3 What are current postsecondary chemistry instructors' thoughts, suggestions, and strategies for improving metacognition in their students?

Q4 How are these postsecondary chemistry instructors' views on metacognition related to their approaches to teaching, as measured by the Approaches to Teaching Inventory?

Sampling

I conducted purposeful sampling of chemistry instructors from various universities and colleges across Colorado. I emailed all the instructors in the chemistry departments from seven different institutions of varying size and Carnegie rankings, and received responses from instructors at six institutions [See Appendix A for email invitation]. The student populations at these six schools varied from 6,000 to 30,000 undergraduate students. Five of the six schools' undergraduate student populations had a majority of white students, with the percentage of students who identified as a person of color varying from 22.5% to 46% among these schools. The school with less than 50% white students also had a large percentage of international students, which were not included in the percentage for white students or persons of color, since an international student could fall under either category. Only one of the six schools was an Hispanic-serving institution (HSI) when I conducted the interviews. For all but one of the schools the majority of the student population identified as female. The six schools had the following Carnegie rankings: three were classified as a “Doctoral University: Very High Research Activity”, one was classified as “Doctoral University of High Research Activity”, one was classified as “Doctoral/Professional”, and one was classified as “Masters Colleges and Universities: Medium Programs”.

IRB approval was obtained from the University of Northern Colorado Institutional Review Board before contacting any potential participants about the study [See Appendix B for IRB approval letter]. All participants gave informed consent before participating in the study. After the interview I sent participants a link for an Amazon gift card to thank them for their willingness to participate in the study.

Data Collection

For this study, I collected multiple forms of data. Since it was a qualitative interview study the main source of data were interview recordings, which were transcribed verbatim, except for stammering phrases such as “um” which were removed for clarity. The interviews followed a semi-structured interview guide. In semi-structured interviews, the interviewer brings a list of questions to cover in the interview, but the interviewer does not have to follow the exact order of the guide or ask all the questions. This type of interview allows for the interviewer to ask additional probing questions of the participant, and to make in-the-moment decisions about the relevance of some of the interview questions, based on what the interviewee has said. I kept detailed notes about which questions I skipped in each interview—

if I skipped any of them—and which questions seemed unclear to the instructors, so that I could improve the questions' wording if necessary, between interviews.

I interviewed 17 chemistry instructors and reached data saturation, which was determined by observing no new major themes. Before the interview I asked participants to send me an example exam question which they felt best exemplified if a student "got it" in regard to the main material. I collected and analyzed the exam questions as artifacts. During the interview, the participants had the option of writing in a Livescribe (Linenberger & Bretz, 2012) notebook if they needed to demonstrate any calculations or needed to write or draw to explain what they were saying. Many did use the Livescribe notebook to work out their test question problem, or to write down their thoughts related to later questions in the interview, though not all instructors wrote in the Livescribe notebook. Their entries in the Livescribe notebook were also recorded and analyzed as artifacts.

The interview protocol [See Appendix C] was designed to move through four phases. First, I asked participants introductory questions, such as "What are the courses that you teach?". The introductory questions were meant to be simple, easy questions to help the participant feel comfortable discussing their teaching practices. Next, I asked the instructor to discuss the exam question they provided. Some of the questions I asked in this portion of the interview are: "What knowledge or reasoning skills were you expecting students to demonstrate with this question?" and "Would a partial answer to the test question tell you anything about the student? If so, what?" In this portion of the interview, I was hoping to hear the instructor discuss their students' thought processes. While the instructor discussed what they hope their students would think about while working through the exam question, I was able to observe whether or not the instructor discussed anything metacognitive, without explicitly prompting them to discuss metacognition. Once the test question discussion was finished, I began asking questions that were trying to implicitly discern the instructor's thoughts on metacognition without using the term "metacognition" or "metacognitive". The reason for this implicit prompting was to prevent instructors' responses from being affected by desirability bias (i.e., where they would talk about metacognition just because they thought that was what I wanted to hear, not because they thought it was most important or relevant.) Examples of questions from this portion of the interview are: "What does a student need to do to be successful in your class?", "Do you expect your students to be self-motivated and self-regulatory?", and "What does a self-motivated and self-regulated student look like to you?". After attempting to uncover the participant's thoughts on metacognition implicitly, I moved to the final phase of the interview where I discussed metacognition explicitly with them. I began this portion of the interview by asking if the instructor had heard of metacognition or metacognitive skills. If they had, I asked them to describe metacognition and metacognitive skills. If the instructor was unfamiliar with these terms, I gave them a brief description so that we could discuss their thoughts on the importance of metacognition. Examples of questions from this section of the interview are: "Do you do anything to specifically develop metacognitive skills in your students?", and "Is it your responsibility to teach students about metacognitive skills? Why or why not? If so, what does that look like?". I concluded the interview with a brief discussion with the instructor about their ideas for how chemistry instructors can improve metacognition development in chemistry students, and any barriers the instructor has experienced in trying to learn about metacognition or teach their students about metacognition.

Throughout data collection, the original interview protocol was iteratively analyzed and revised to ensure I was asking questions that would elicit responses that could provide answers for the study's research questions. After the first interview, I expanded the second phase of the interview in which the instructor discussed their exam question to include three more questions that focused on what the instructor hoped students' thought processes would be. After testing these questions out in the second and third interview, I determined that two of the three questions were eliciting useful responses, and so I cut the third question that was not eliciting much from the participants. The questions that I kept were: "What knowledge or reasoning skills were you expecting students to demonstrate with this question?" and "Would a partial answer to the test question tell you anything about the student? If so, what?". After the fourth interview, I reflected on the data collected and realized that the third research question, "What are current postsecondary chemistry instructors' thoughts, suggestions, and strategies for improving metacognition in their students?" was not being addressed by participants from answering the current interview guide. Thus, I added two questions to the end of the interview guide, "How can we (chemistry instructors) improve the development of metacognition in chemistry students?" and "What are some barriers that you have experienced to being able to develop metacognition in your students?". I had also noticed in the first four interviews that participants described their first day of class talk as a time when they communicated expectations of their students and described good habits and practices for studying for the course. In these discussions, the instructors touched on things that were metacognitive, and so

I added a question that explicitly asked the instructor to describe their first day of class "class expectations" talk. I tested this question in the fifth and sixth interviews, and unfortunately the question did not elicit responses that included anything metacognitive, and so I cut it before the seventh interview. While reflecting after the eighth interview, I noticed a theme in the first eight interviews that instructors frequently described a difference in students' thinking depending on their age, whether they were freshmen versus seniors, or traditionally-aged college students versus non-traditional college students. To explore this idea further, I added the question "Do you see a difference in students' study habits/skills depending on their age? Either traditional students versus non-traditional students or lowerclassmen versus upperclassmen?" to the interview guide before the ninth interview. In the following interviews this question elicited interesting answers relevant to students' metacognition, and so I kept the question. The last change I made to the interview guide was to remove the question "What level of self-efficacy would you say your students have?". I removed this question after the first eleven interviews, because I realized many instructors were unfamiliar with the concept of self-efficacy. In the interviews, I had struggled to clearly describe the concept, and so the responses to the question were not helpful or relevant to this discussion on metacognition development.

The interviews lasted between 30 minutes and an hour and 20 minutes in length. I informed the professors of the confidentiality measures taken to protect their identity, and I asked them to sign a consent form [See Appendix D] that gave their permission for their recordings and artifacts to be used in my research. I also collected the participants' demographic information [See Appendix E]. About a year after the interviews, I collected survey data from my participants by inviting them over email to complete the Approaches to Teaching

Inventory (ATI) (Trigwell & Prosser, 2004; Trigwell et al., 2005) via a Qualtrics survey. [See Appendix F for the ATI questions, and Appendix G for IRB approval to include ATI, and appendix H for the consent form for the ATI]

Data Analysis and Analytical Framework

I analyzed the interview data by employing Braun and Clarke's (2006) reflexive thematic analysis process to define themes in the data. To familiarize myself with the data, I transcribed and annotated the interviews with descriptions of what the instructors drew or wrote in the Livescribe notebook, and I wrote a summary of each interview. In the summary of an interview, I would copy and paste interesting sections of the transcript and include my initial thoughts about how the quotes I was pulling out of the interview may relate to metacognition. I especially looked for any instances of an instructor describing their own metacognition, their students' metacognition, or expectations they had for their students that required their students to be metacognitive. I also looked for repetitive ideas throughout each individual interview, and ideas that were similar to other interviews I had analyzed. After writing the summary of an interview with my initial thoughts on analysis, I imported the transcript into NVivo 12 (https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home), where I began to generate codes. I first would annotate the interview in NVivo 12 with the thoughts from the summary, by creating detailed memos attached to the specific quote. I then began creating codes by reading through the transcript again, and each quote that stood out was assigned a very specific descriptive code of the quote. In the annotations for a quote, I would include a description of my thought process in creating new codes and assigning existing codes to a quote. Not all codes were created inductively; I also deductively coded the interviews for instances of metacognition. These deductive codes were created and based off Zohar and Dori's (2012) definitions of these terms. When coding instances of metacognitive knowledge or skills, I would code either "metacognitive knowledge" or "metacognitive skills" as the top-level node, and which specific type of metacognitive knowledge or skills as a subnode. Metacognitive knowledge has three subtypes: procedural knowledge, conditional knowledge, and declarative knowledge. Procedural knowledge is knowing how to employ a learning strategy. A student could have knowledge of how to make flashcards, or how to best organize their notes, which are both learning strategies. Any instances of instructors describing knowledge of learning procedures was coded as *metacognitive knowledge*, *procedural knowledge*, and then a more specific code describing the instance of procedural knowledge was assigned. Examples of specific *procedural knowledge* subnodes were: "learn by doing", "student knows how to study", and "Keep it Simple". Conditional knowledge is knowledge of when to apply a learning strategy. For example, when a student knows the best way to study for a math exam is to practice the type of problems they have been learning, and that reading the textbook is the least productive study method, the student is employing their conditional knowledge. Any instances of an instructor describing conditional knowledge was coded as *metacognitive knowledge* and *conditional knowledge*, and a more specific code was also assigned to describe the instance of conditional knowledge. Examples of specific *conditional knowledge subnodes* are: "applies appropriate learning strategies", "developing conditional knowledge", and "lacks knowledge of when to apply a learning strategy". The last *metacognitive knowledge* code is *declarative knowledge*. Declarative knowledge is knowledge of one's own cognition, or an awareness of one's knowledge and knowledge limitations. People with strong declarative knowledge are aware of the information they do not know, and the level of knowledge they have regarding topics of which they are familiar. If someone was asked if they could name all the first 50 elements on the periodic table, they would engage their declarative knowledge to judge whether they know that information. I coded all instances of instructors discussing declarative knowledge as *metacognitive knowledge*, *declarative knowledge*, and a specific code describing the instance of declarative knowledge. Examples of subnodes of *declarative knowledge* are: “instructor expects students to be aware of their knowledge limitations”, “Student unaware of limitation of their knowledge”, and “developing declarative knowledge”.

There are five types of metacognitive skills: planning, information management, monitoring, evaluating, and debugging. The first subnode, *planning,* is the ability to develop a plan for how to complete a task before beginning it. Metacognitive planning also includes the ability to allocate resources before beginning a task, and goal setting for a task. For example, if a student was answering a stoichiometry homework question, and they identified the goal was to calculate the gram amount of a product in a chemical reaction, that would be goal setting. The student could allocate resources in this example task by remembering they need the molar mass of the substances involved, and by deciding to calculate those values prior to beginning. They could plan by considering what they would need to do to find the amount of product, such as remembering they will need to convert grams to moles, and then convert from moles of one substance to another, etc. I coded any occurrence of instructors discussing planning skills with the codes *metacognitive skills*, *planning*, and a specific subnode of planning that describes the occurrence. Examples of specific *planning* subnodes are: “resource allocation while completing a task", "instructor expects students to plan", and "students lack ability to plan". The second subnode was *information management*. Zohar and Dori (2012) define the metacognitive skill of information management as "Skills and strategy sequences used on-line to process information more efficiently" (p.60). When students have a particular strategy for organizing information given to them in a problem, such as drawing a diagram, using curved arrow notation to understand the movement of electrons, or writing out a balanced equation for a reaction, they are using information management. When an instructor described a strategy for organizing information, I coded it as *metacognitive skills*, *information management*. In the instructor study, there were very few occurrences of the information management code, thus I did not create any descriptive subnodes for this code. The third metacognitive skill, monitoring, takes place during a task. A student employs monitoring when they keep track of their understanding while completing an activity or when they notice when something is not what they expected. Good cooks employ monitoring while making a meal. They are aware when the process of making a dish is going well, or when problems arise. For example, a good cook would notice if the meat is cooking properly, or if the seasoning is not quite the right flavor, during the process of making the meal. A bad cook who does not monitor their work would just blindly follow a recipe, without noticing if the dish they were preparing looked and smelled the way it should at different steps along the process. I coded any discussion of monitoring from the interviews as *metacognitive skills*, *monitoring*. Since monitoring happens mid-task, and my interview protocol did not require instructors to discuss their thoughts or appraisal of what they were doing while they were doing it, monitoring had very few occurrences in the interviews, and thus did not have any specific subnodes. The fourth metacognitive skill I coded for is closely related to monitoring and is called evaluating. The main difference between monitoring and evaluating is that evaluating takes place after the task is completed. To continue with the cooking analogy, monitoring takes place while the meal is being prepared, but evaluating takes place once the meal is finished, when the cook samples the final dish and decides if it was properly prepared. Students use the evaluating skill when they complete an activity or assigned problem and decide if their answer makes sense and if their work looks correct. I coded all occurrences of evaluating, as *metacognitive skills*, *evaluating*, and a specific subnode to describe the instance of evaluating. There were many subnodes of *evaluating*. A few examples of these subnodes were: “Instructor wants students to self-evaluate and make changes”, “Instructor evaluates their teaching”, and “students lack the ability to evaluate their understanding”. The last metacognitive skill I coded for is debugging. Debugging can take place while a student is monitoring or evaluating. Debugging occurs when a student encounters an issue in their work, and they try to fix the issue. Thus, it is possible for students to be made aware of issues during the process (while they are monitoring) or at the end of the process (when they are evaluating their work). In either case, a student employs debugging when they identify the problem and try to determine a solution. I coded instances of debugging as *metacognitive skills*, *debugging*. There were very few occurrences of instructors discussing debugging, and so I did not create any subnodes for the debugging code.

As I coded the interviews, some over-arching themes were identified in the data. I began to group similar ideas represented by the very descriptive codes together under general top-level nodes. One of the general ideas was the code “how instructors value metacognition”. While I was coding for specific instances of metacognition, it became apparent that in some of the instances the instructors in their descriptions were assigning value to the things I was coding as metacognition. Thus, this separate code was identified, specifically for quotes where an instructor described something I had coded as metacognitive, that they thought was a good or bad practice for their students. While analyzing for instances of metacognition, I observed another over-arching theme. There were multiple instances of metacognition that I was coding that were specifically recommendations instructors made to students, or activities these instructors implemented in class that developed their students' study habits and learning strategies, and consequently, their metacognition. Especially when considering my research questions, I thought it was important to have a separate code for how these instructors were developing their students' metacognition, and so I created the top-level code "developing metacognition and learning strategies". While discussing their methods for developing their students' metacognition, instructors frequently mentioned barriers they experienced to successfully implementing activities that could develop metacognition. As discussed in the interview guide development above, the explicit question "What are some barriers that you have experienced to being able to develop metacognition in your students?" was added after the fourth interview. I grouped the instructors' responses to this question along with their descriptions of barriers to metacognition from earlier in the interview under the top-level code "barriers to metacognition". There were a few more descriptive codes that I created while coding metacognition instances in the interview, but they did not fit into an over-arching theme with other codes. These codes were "Kruger-Dunning", "metacognition in test question", "metacognition outside the classroom", "metacognitive experiences" and "instructor's own metacognition". I coded "Kruger-Dunning" anytime an instructor discussed their students' metacognition and either mentioned the Kruger-Dunning effect or described a scenario that was an example of the Kruger-Dunning effect (i.e., poor performing students overestimating their performance). I used “metacognition in test question” to keep track of instances of metacognition that specifically came up when the instructor was discussing the exam question they brought to the interview. I created the code “metacognition outside the classroom” to keep track of quotes describing metacognition outside of the classroom setting, since the majority of the metacognition discussed in these interviews focused on a classroom setting. “Metacognitive experiences” is mentioned in some of the literature as a type of metacognition but is not included in all discussions of metacognition (Efklides, 2006; Flavell, 1979; Schraw & Dennison, 1994; Zohar, 2012). I created this code early on because of what I read about metacognition in the literature, but because of the nature of these interviews, it was rare to have many quotes that described a metacognitive experience, which is when students or instructors face a challenging experience that requires them to engage their metacognition. “Instructors’ own metacognition” was coded in quotes where the instructor specifically discussed how they think about their thinking. There were a few other codes created purely to help with organization: “before metacognition definition”, “after metacognition definition”, “level of knowledge of metacognition”, and “reminds me of another instructor interview”. The first two codes were useful in keeping track of when a quote occurred in the interview. All quotes before the explicit metacognition discussion were coded as “before metacognition definition” and all quotes after the explicit metacognition discussion were coded as “after metacognition definition”. The very beginning of the explicit metacognition discussion, when I asked the instructors “Are you familiar with the term ‘metacognition’?” was coded with “level of knowledge of metacognition", so that I could quickly reference if an instructor knew what metacognition was or if I had to define the term for them. The last organizational code "reminds me of another instructor interview" was particularly helpful when I was looking for repetitive themes among the different instructors' interviews.

There were also recurring themes that did not necessarily relate to metacognition, but were present in many of the interviews, and so were coded. However, we did not make any claims based on these codes. These codes were "cognition", "proficient student habits", "non-proficient student habits", "ownership of learning", and "student characteristics". "Cognition" was most commonly coded in the exam question discussion, when instructors would discuss what they wanted students to focus on when answering the question, or what the student should know in order to answer the question. "Cognition" was coded whenever the instructor discussed what they thought students were thinking about during the test question, if that discussion did not include thinking about thinking, but merely thinking about class concepts. "Proficient student habits" and "non-proficient student habits" were usually coded in response to the questions about an ideal student for the instructors' courses. Some of the quotes with these two codes were metacognitive, but that was not always the case, so they were not grouped in with any metacognition codes. Instead, if there was metacognition present in a quote about proficient student habits or non-proficient student habits, I also coded that quote with the appropriate code of "metacognitive knowledge" or "metacognitive skills" and the appropriate subnodes. "Ownership of learning" was a fairly common idea discussed in ten of the interviews, but this idea did not necessarily relate to how students think about thinking, so it was not grouped in with other metacognitive codes. Lastly, the "student characteristics" code was used for statements that described a particular student group. Some of the characteristics that were coded were “freshmen are not as successful in college as older students” and “seniors are more metacognitive than younger students”. This code was created because there has been evidence in the literature that metacognitive development may vary with age and experience (Dye & Stanton, 2017; Stanton et al., 2015, 2019), and so I wanted to be able to capture any of these trends in this code. Unfortunately, many of the statements about student characteristics were unique to individual interviews, and so there were no trends observed with this code, even though fifteen of the seventeen instructors discussed thoughts about the characteristics of specific student groups.

There was one code that overlapped between the idea of metacognition and cognition. While coding, I noticed multiple instances where instructors discussed activities or assignments that they identified as being metacognitive without actually discussing any metacognition related to that activity or assignment. This phenomenon was present in twelve of the interviews, and so I created a code for it called “instructor mistakes cognition for metacognition”. I discuss this code and its implications in more detail in the results section.

The last top-level code that I added to the codebook was “suggestions for metacognition development”. After I had finished coding all seventeen of the interviews and had started to compile my results, I realized there was not a specific code that addressed RQ3: “What are current postsecondary chemistry instructors’ thoughts, suggestions, and strategies for improving metacognition in their students?”, specifically the “suggestions” part of this RQ. The “developing metacognition and learning strategies” code did not only include quotes where instructors explicitly described their suggestions to encourage metacognition in chemistry students. Many of the quotes in the “developing” code were descriptive of activities that the instructor did not necessarily identify as metacognitive, so I did not feel it was appropriate to use these quotes as “suggestions for improving metacognition in their students”. There was a question in the interview guide that explicitly asked instructors “How can we (chemistry instructors) improve the development of metacognition in chemistry students?”. The instructors’ responses to this question explicitly addressed their thoughts and suggestions for how to develop chemistry students’ metacognition, so I concluded that to answer RQ3, I needed a code that applied to just the responses to this question. Thus, I created the code “suggestions for metacognition development” which I only coded for instructors’ responses to the above question.

I iteratively reviewed the codebook throughout the coding process. During a review of the codebook if I realized a code’s definition needed to be changed or clarified, I would go back through each interview I had already coded and re-apply the new definition of the code, to make sure coding was consistent. Below, I discuss other measures taken to ensure the reliability of my coding and analysis.

After analyzing all of the interviews and reviewing the codebook to identify the major themes defined in the data, we investigated relationships and trends between codes and according to the contextual features we had collected in demographic information by using the matrix coding function in NVivo 12. This function allowed us to group the interviews and their codes by the demographic information, to observe any trends related to teaching experience, school size, and subject taught. We were also able to observe any trends in coding when the instructors were sorted by different codes, for example, by their knowledge of metacognition.

I also analyzed the ATI survey data. The ATI consists of 16 survey items, which participants responded to by selecting one of the five options: (1) Rarely or never true, (2) sometimes true, (3) true about half the time, (4), frequently true, (5) almost always or always true. To score the participants' responses to the survey, their responses were assigned the numbers listed above. There are two main scales measured by the ATI, each with eight items. The two scales measure instructors' approaches to teaching and categorize them as employing teacher-centered information transfer practices (ITTF) or student-centered, conceptual change practices (CCSF). To calculate the score for each scale I summed each participant's response to those eight items, which should produce scores ranging from 8-40 on both scales. Higher scores on the ITTF scale would indicate that the instructor frequently employed lecture and information-transfer teaching practices, while high scores on the CCSF scale indicates an instructor is more likely to employ student-centered teaching practices, with the goal of conceptual change. The results from the ATI data analysis are reported in Chapter 6 of this dissertation.

Validity and Reliability Measures

Throughout data collection and analysis, various measures were taken to ensure validity and reliability of the data and its analysis. During data collection, I kept a written record of my thoughts, observations, and initial analysis of the interview data, by taking time to reflect and record these thoughts after completing each interview, and after the first listen-through of the interview recording. Also, during data collection, I collected multiple sources of data from participants, allowing for triangulation in the data analysis process. Throughout data collection and analysis, I kept a research journal to log my thoughts regarding recurring themes emerging in the data, development of the codebook, and explaining the definition of specific codes and when they should be applied. I also met weekly with my research advisor, Dr. Weinrich, to discuss the data collection process, changes to the interview guide, data analysis, and the development of the codebook. During data analysis, I recorded specific and detailed memos in NVivo while coding the data, to ensure I applied the codes to similar instances across the interviews, and that the definitions of the codes remained consistent throughout the coding process. After I completed data analysis, my research advisor, Dr. Weinrich, conducted an inter-coder reliability study, by coding 20% of the interviews. I met with Dr. Weinrich to discuss her coding in the inter-coder reliability study. Initially, our coding differed by 20%, but we discussed these differences until agreement was reached.

This study is not generalizable, since it is a qualitative interview study with only 17 participants. However, the goal of this study was to instead present research that is transferrable (Merriam & Tisdell, 2016) by presenting a rich description of the data and analysis process so that the reader can discern how this research is relevant to their own research and teaching practices.

Part B: Biochemistry Student Study

Purpose of Study and Research Questions

The goal of this study was to observe how biochemistry students responded to questions aimed at implicitly activating their metacognition while solving buffer problems. As discussed in the literature review in chapter 2, the majority of metacognition research in CER has focused on general chemistry students. I chose to study students in an upper-division biochemistry course to expand what is currently known in the field to include biochemistry students. I also believed it would be worthwhile to interview upper-division students (juniors and seniors) because of the research conducted by Dye and Stanton (2017) and Stanton et al. (2019). They have found that upper-division biology majors are usually more metacognitive than introductory biology students. Thus, I expected to be able to observe metacognition in the majority of these interviews with upperclassmen, whereas a study with lowerclassmen may not have been as rich in metacognition, according to Stanton et al.'s (2019) findings in biology education.

The research questions guiding this study are:

Q1 How do undergraduate biochemistry students employ metacognitive skills when solving buffer problems?

Q2 How do undergraduate biochemistry students employ metacognitive knowledge when solving buffer problems?

Q3 In what ways does implicitly targeting metacognition change a biochemistry student's metacognitive approach to solving buffer problems?

Sampling

I conducted purposeful sampling of upper-division biochemistry students from a mid-size public university in the Rocky Mountain region of the United States. After receiving approval from the Institutional Review Board of the University of Northern Colorado [See Appendix I for IRB approval letter], I contacted the biochemistry professor who was teaching the 300-level biochemistry course and asked permission to recruit students from their course to participate in an interview study. I discussed with the professor if it would be possible to offer a small amount of extra credit to the students who participated in the study, and they were kind enough to agree to do so. I also had an alternative extra credit activity for any students in the course who did not want to participate in the study but wanted to earn extra credit for the course.

I recruited students to participate in this interview study by making an announcement at the start of one of the lecture class periods. I briefly described the study, telling the students that to participate, I would interview them and ask them to solve two biochemistry problems while thinking aloud. I also told them that participants would receive extra credit as an incentive to participate. After making my announcement, I passed around a sign-up sheet where students who were interested could sign up by giving me their name and email address. I then emailed all the interested students a link to a Doodle poll, where they could sign up for a day and time to be interviewed [See Appendix J for copy of the email invitation]. The day before their interview, I sent each participant a reminder email. At the interview, I began by obtaining students' consent to record their interview for my research [See Appendix K for the consent form]. I explained to the students the measures I would take to ensure their identity remained confidential and made sure to answer any questions they had before having them sign the consent form. If a student was not comfortable signing the consent form, I told them they could still receive their extra credit by completing the alternative assignment. Twenty-six students consented to participate in this study (out of 71 students enrolled in the course).

Data Collection

For this study, I conducted 26 in-person interviews with students from an upper-division biochemistry course at a mid-size university. I collected multiple sources of data during the interview: audio recordings which were later transcribed, Livescribe drawings of the students' work, demographic data, exam score data, and survey data using the Revised Study Process Questionnaire (R-SPQ-2F) (Biggs et al., 2001) [See Appendix L for a copy of the R-SPQ-2F].

The interview guide was semi-structured, similar to the previous study in this chapter. The main difference from the structure of this interview guide was that there were specific questions that were asked at each interview and in the same order at every interview. What differed from interview to interview were the probing questions I chose to use. On the interview guide, I had a list of possible probing questions and depending on what the student had said so far in the interview, I chose different probing questions as they felt appropriate. This interview protocol was developed with the goal of observing how different prompts or questions might encourage a student to be metacognitive while solving buffer problems. The first phase of the interview guide simply asked students to solve a buffer problem while thinking aloud and writing their work and ideas on a Livescribe notebook. In the second phase, students were asked to read the second problem but wait to begin working on it. After the student read the second problem, I asked them questions about "another" student that might attempt this problem but somehow go astray in their solution. There were five questions about this "other" student and what they might think about. Two of those questions were from the study Talanquer conducted in 2017, where he had students "'Select the option below that you think is most commonly chosen by students who get this question wrong because they do not carefully reflect on what the question is asking or are misguided by their intuition.'" (Talanquer, 2017, p. 1807). To adapt this prompt to our interview guide, we split it into two separate questions: "Can you describe how a student who 'does not carefully reflect on what the question is asking' might work through the problem?" and "Can you describe how a student who is ‘misguided by their intuition’ might think about and answer this problem?” After students answered the five questions about “another” student, they were asked to work through the problem while thinking aloud. After they had completed their work on the problem, I repeated the first question from phase 2, asking if they had any new ideas on how a student might go astray after working on the problem themselves. The purpose of phase 2 was to implicitly elicit metacognition in the student and to observe if the student discussed anything metacognitive while describing the other student’s thoughts, and to observe if the implicit metacognitive prompting changed their approach to solving the second problem. For the complete interview protocol, see Appendix M.

To test whether this interview protocol would be useful in observing students’ metacognition, I conducted a pilot study with two general chemistry students. I met with each student individually, and instead of having them solve buffer problems, I picked problems from the American Chemical Society’s (ACS) General Chemistry exam review book (Eubanks & Eubanks, 1998). The timing of the pilot study was near the end of the course, and so to recruit students I thought it would be beneficial to use questions that could also help them review for their final exam. I recorded the pilot study sessions so that I could review and take notes on how the students responded to the interview protocol but deleted those recordings after I had gleaned enough information from them to inform the development of the interview guide. In both pilot study interviews, the students made statements that indicated they were thinking about their thinking. The main change that was made to the interview after the pilot study was not the questions, but how I delivered them. Prior to the pilot study I was concerned about word clarity in some of the questions, but both students had no problem with understanding the questions, and so I realized I did not need to preface any of my questions with a statement like, “Please tell me if this question is confusing,” and instead just asked the questions as they are written in the interview guide and left it up to the participants to ask clarifying questions as needed.

To finish preparing the interview protocol for biochemistry students, I needed to select two buffer problems of appropriate difficulty level. After meeting with the instructor of the biochemistry course to gauge students’ experience with buffers in this biochemistry class, I picked two buffer problems from the Chemical Thinking curriculum (Talanquer & Pollard, 2010, 2017) with permission from the creators of the curriculum. I met again with the course instructor and we reviewed the questions, and the instructor believed the questions to be an appropriate difficulty level. These are the questions that were selected:

Buffer Design: “*Buffers can be prepared by directly combining the acid/base conjugate pair or by inducing reactions that generate them in solution. Imagine that you wanted to prepare a buffer containing equal concentrations of* HNO_2 *and* NO_2^-*. These are the substances you have available to complete your task:* H_2O*,* HNO_2*,* KNO_2*, HCl, NaOH. Propose three different strategies to prepare the targeted buffer. Justify your reasoning.”*

Buffer pH: “*Imagine that you use 0.6 moles of HCN (pKa = 9.2) and 0.5 moles of NaCN to prepare two different buffer solutions. In one case you add these amounts to a beaker with 100 mL of* H_2O*. In the other case, you add the same amounts to another beaker with 200 mL of* H_2O*. Which of the two buffer solutions will have a lower pH? Clearly justify your reasoning.”*

(Talanquer & Pollard, 2015, p. 394)

Since the questions asked students to do fairly different work with buffer solutions, I alternated the order of the questions in the interviews, so that half of the students answered the questions in the above order, and half of them answered in the reverse order.

Before beginning the interview with a student, I first discussed the consent form and made sure they were aware of the data I planned to collect from them. I specifically told them I would be recording the session, and that at the end of the session I would ask them to fill out a survey on their study habits, and a demographics form. I also made sure they were aware that by signing the consent form they were giving me permission to request their first exam's score from the course instructor. The instructor believed this score would be most relevant to the students' understanding of buffers in the context of the class, because buffers was a concept covered very early in the semester. As I described in the sampling section, I made time for students to ask any questions, and if they were uncomfortable with providing any of the information I needed for the study, I suggested they complete the alternative extra credit assignment instead. In the consent form discussion, I also explained to students how I would maximize their confidentiality as a participant in this study. Their real names were not associated with any of the data, and instead I gave each student a code that was used to label all their data. I kept one hard copy list of the participants and what code had been assigned to them, in case I needed to contact them for any reason after the interview. This list was kept in my advisor's office in a locked drawer, along with the signed consent forms. I told the students that the instructor for the course would know they had participated so that I could obtain their exam scores, and so that the instructor could give the students their extra credit. I made sure to emphasize that the instructor would not have access to any of the data or information collected from each participant's interview, simply that they participated. After completing the interviews, I gave the instructor a list of all the students who participated in the study and who completed the alternative extra credit assignment. I then met with the instructor in person to obtain the exam scores for each student who gave consent, so that the exam scores were not sent over email.

During the interviews, I recorded the audio and had students write in a Livescribe notebook, which recorded what they were writing and what they were saying. The audio was transcribed by undergraduate transcribers and by an online transcribing program, temi.com. After the transcripts were completed, I then analyzed the Livescribe drawings and added detailed annotations to the transcripts describing what the student wrote while they were talking, along with screen captures of the drawings. After completing the questions from the interview protocol, I had students respond to the Revised Study Process Questionnaire (R-SPQ-2F) (Biggs et al., 2001), in order to obtain more data regarding their study habits [See Appendix L for the R-SPQ-2F survey items]. Lastly, I collected demographic data from the students [See Appendix N for the demographic form]. The interviews lasted between 21 minutes and 1 hour and 6 minutes, with the average length of the interview lasting 39 minutes.

Data Analysis and Analytical Framework

I employed Braun et al.'s (2019) "codebook thematic analysis" method to analyze the interview data. Once the interview recordings had been transcribed and annotated with the Livescribe drawings, I began analyzing the interview data by reading through each interview and creating a summary of the metacognition I observed in each interview, and any recurring and important ideas I found. While summarizing interview number four, I realized that this interview needed to be removed from the data set. During the fourth interview, when we reached the second buffer question and I asked the student to solve the problem, he responded that he did not want to do so. To try and encourage him to work on the problem, I began to ask questions to prompt his thoughts, and they were very leading. Because of this, we decided that the data in this interview had been corrupted and thus removed the interview from the data set. I continued the analysis with the remaining twenty-five interviews. Once I had completed all the summaries, I imported the interview transcripts into Nvivo 12 (https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home) and began coding the data. I conducted multiple rounds of coding. The first round was a deductive analysis process; I applied the Zohar and Dori (2012) framework of metacognition to the data, searching for and identifying any instances of metacognitive knowledge (procedural knowledge, declarative knowledge, conditional knowledge) and metacognitive skills (planning, information management, monitoring, debugging, and evaluating). While I analyzed the interviews for the deductive codes, I added inductive codes to the codebook as I found them in the data set. Many of these codes were inspired from the notes I had taken in the summaries on interesting things I noticed in the dataset. After writing the summaries for all the interviews I could be confident when an idea was present in more than one interview. Thus, the majority of the inductive codebook was built from the information in the summaries, and during the deductive coding phase. After deductively coding all twenty-five of the interviews, I re-analyzed them for any inductive codes that I found in the data by going through each interview again and searching for instances of the inductive codes I had created. Along with coding for the inductive codes, I also coded “organizational” codes, so that I could easily refer to different sections of the interviews or group the students' responses to the two different buffer problems (e.g., the first problem was coded with "HNO2" and the second problem was coded with "H-H", which stands for Henderson-Hasselbalch, so that I could easily call up all of the responses to either of those questions.) After I finished the inductive round of coding, I assessed the students' responses to the two buffer problems for their accuracy, essentially "grading" their responses. I created a rubric on the scale from 0-3 for both questions by reading through all the students' responses for the question and grouping similar responses, and then ranking those groups (for the detailed grading rubric, please see Appendix O). Everything the student said and wrote down while solving the problem was reviewed for their assessment score. After grading, I reviewed the codebook, and identified codes that could be consolidated into groups of similar ideas. I also identified which codes were representing the major themes that I had found in the analysis and reviewed all the quotes in those codes for consistency.

The codebook was built from deductive and inductive coding schemes. Zohar and Dori's (2012) framework of metacognition was the basis for the deductive codes. Metacognitive knowledge and metacognitive skills were top level nodes in the codebook, with each of their subcategories being subnodes. When I found an instance of a specific type of metacognition, I also created a subnode to describe the instance of metacognition. Similar to my analysis of the instructor study discussed earlier in this chapter, each quote that demonstrated a student's metacognition was coded with either "metacognitive knowledge" or "metacognitive skills", the specific type of metacognition, and a descriptive subnode. For examples of some of the descriptive subnodes created for the eight different metacognition codes, see Table 3.1.

Table 3.1

Metacognitive Knowledge and Skills Descriptive Subnodes

Metacognitive Knowledge (MK)	
Type of MK:	Examples of descriptive subnodes
Conditional Knowledge	• When the student feels rushed or hurried on an exam, they know to employ certain learning strategies • When no equation is provided, need to draw to visualize what's happening
Procedural Knowledge	• Strategy: write down or underline important information in a question • Strategy: draw pictures to visualize and understand the problem
Declarative Knowledge	• Know what they know • Know what they do not know
Metacognitive Skills (MS)	
Type of MS:	Examples of descriptive subnodes
Planning	• Goal setting • Allocating resources
Information Management	• Describes using their information management skills • Writing or drawing to process information more efficiently
Monitoring	• Appraisal of thought process • Awareness of assumptions
Debugging	• Strategy: simple solution • Strategy: review your work
Evaluating	• Identifies areas where they struggled in solving the problem • Reflects on answer/work and finds an error

I identified multiple inductive codes in the data, which were consolidated into a few major ideas. The first major idea was "Beliefs about learning and assessment", which included quotes where students expressed their beliefs about how they learn best, how exams should be structured, and a small number made statements indicating they valued metacognition. Unfortunately, each of these ideas were only present in a small number of interviews. Thus, after completing the inductive coding for these beliefs, I decided that the over-arching idea of “beliefs about learning and assessment” was not present in a sufficient number of interviews, and that the ideas expressed were not incredibly relevant to the research questions, so these codes were excluded from further analysis.

Another major idea that I identified during the inductive coding process was “metacognitive experiences”. According to Efklides (2006), metacognitive experiences are the overlap between metacognition and the affective domain. Thus, I coded statements of feeling with “metacognitive experiences”. Many of the statements conveyed feelings of uncertainty or seemed to demonstrate the student’s self-efficacy with regards to chemistry and buffer problems. After coding all of the interviews for metacognitive experiences, there did not appear to be any cohesive trends or interesting ideas relevant to the research questions.

The last two inductive codes were part of the same idea and were almost exclusively coded in the second part of the interviews, during the implicit metacognitive prompting questions. When students were asked to discuss the “unreflective” student, some students answered the question from their own perspective, others clearly discussed an “other” student, and for some it was unclear who the subject of their discussion was. To tease out the differences I was observing, I created the code “Voice” with subnodes “first person”, “second person”, “third person”, and “voice unclear”, and then coded students’ responses to the metacognitive prompting questions. Upon further investigation, I realized some students were making statements that might be metacognitive, except for the fact that they used parts of speech that did not indicate they were speaking of their own thinking processes (they used “you” or “they” instead of “I”). Because these statements were not made in first person, I felt uncomfortable coding them as metacognitive, but instead created the code "transitional metacognition" to capture this idea.

The other codes that were included in the codebook were "organizational" codes to easily identify which buffer problem the student was solving, if that problem was the first or second problem in the interview, and to easily refer to the probing questions I asked throughout the interview, to make sure I did not ask any leading questions. We also created the code "codable unit" so that during inter-coder reliability (ICR) coding Dr. Weinrich could know what chunks of text I had designated as a unit. To determine the size of a codable unit, I referred to one of the methods discussed in O'Connor and Joffe (2020). I coded the text in chunks that were complete thoughts, which varied in size, and was why we decided the "codable unit" code would be beneficial for ICR.

After reviewing the codebook, I gave Dr. Weinrich a copy of the NVivo file and she conducted ICR (O'Connor & Joffe, 2020) measures, which will be discussed in the "Validity and Reliability" section below. After completing ICR, I used the matrix coding function in NVivo to analyze the relationships between the different codes, and to identify any differences in coding from Q1 to Q2 in the interviews, to be able to answer RQ3.

I also analyzed students' responses to the Revised Study Process Questionnaire (R-SPQ-2F) (Biggs et al., 2001). The students responded to this survey at the end of their in-person interview using Akindi bubble sheets. I scanned the Akindi sheets, and the Akindi program produced a spreadsheet of students' responses. There are 20 questions on the R-SPQ-2F, and students chose from five possible responses: (A) Never or rarely true, (B) Sometimes true, (C) true about half the time, (D) frequently true, and (E) Always/almost always true. The Akindi spreadsheet recorded students' letter responses, and I used Excel's "find and replace" function to convert all the "A" responses to "1", "B" responses to "2", etc. When I reviewed the dataset, I found that two of the twenty-five students had filled out their answer sheet incorrectly, and thus had to remove those two responses from the data set. The remaining 23 responses were all filled out correctly and were analyzed according to Biggs et al.'s (2001) instructions. The R-SPQ-2F measures students' approaches to learning on two main scales, which are Deep Approach (DA) and Surface Approach (SA), and four subscales: Deep Motive (DM), Deep Strategy, (DS), Surface Motive (SM), and Surface Strategy (SS). To calculate the scores for the two main scales, I summed individual students' responses to the ten questions that corresponded to that scale, with a possible response range from 10-50. The two main scales in this survey measure students' approach to learning in a specific learning context, in this case their biochemistry course. High scores on the "SA" scale indicate a student is employing a more "surface" approach to learning in this biochemistry course, where high scores on the "DA" scale indicate a student is employing a more "deep" approach to learning in their biochemistry course. The four subscales were calculated by summing five of the questions in the survey that corresponded to that subscale. The "DM" subscale measures the "deep motivations" a student demonstrates in their approach to learning, while the "SM" subscale measures their "surface motivations". The "DS" measures their "deep strategies" for learning, and "SS" measures their "surface strategies" for learning. For all four subscales the possible score range is 5-25, with higher scores indicating the student has that type of motivation or employs those types of strategies. The results from this survey are reported in Chapter 5.

Validity and Reliability Measures

I enacted multiple practices to maximize validity and reliability in this study: triangulation, audit trail, and an inter-coder reliability study (Merriam & Tisdell, 2016; O'Connor & Joffe, 2020). I collected multiple sources of data so that I could triangulate the data analysis. Throughout the development of this study, data collection, and data analysis I kept a research journal and recorded detailed memos, discussing the thought process behind all decisions that were made for the project. (Many of these memos discussed thoughts from the analytical process similar to my memos for the instructor study: thoughts post-interviews, initial ideas of how to interpret the data, coding definitions and consistency, etc.) I met weekly with Dr. Weinrich to discuss my progress in the project, and for the data analysis process met frequently with an undergraduate researcher to discuss the development of the codebook and the analysis of the data.

After I finished coding all the interviews, Dr. Weinrich conducted the inter-coder reliability study by coding 20% of the dataset (five interviews). We met to discuss any differences in coding and were able to reach agreement on those differences. Prior to discussing, there was a 96 % agreement in coding.

Similar to the previous study discussed in this chapter, this research is not generalizable because it is qualitative interview data. In my discussion of these analytical methods, I aimed to provide a detailed description of my sample, data collection and analytical methods so that the reader can have a full picture of how I conducted this study. In the results I will provide a rich description of my interpretation of the results of this analysis. With all this information this research can be transferable—where the reader considers the context of the study, the methods employed, and the interpretation of the results and decides if the results are relevant to their context.

CHAPTER IV

UNDERGRADUATE CHEMISTRY INSTRUCTORS' PERSPECTIVES ON THEIR STUDENTS' METACOGNITIVE DEVELOPMENT

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Abstract

Metacognition is an important skill for undergraduate chemistry students, but there has been scant research investigating chemistry instructors' perspectives of metacognition and the development of their students' metacognition. Since undergraduate instructors have a wide influence over what happens in their courses, it is crucial to investigate their understanding of metacognition, and discern whether they value metacognitive development for their students. This qualitative interview study explored the perspectives of seventeen chemistry instructors who taught chemistry at the college level from six different institutions across Colorado. The interviews were coded deductively according to Zohar and Dori's definitions of metacognitive knowledge and metacognitive skills, and inductively for themes through reflexive thematic analysis. These interviews provided a window into these instructors' personal pedagogical content knowledge (pPCK) and how it influenced their enacted pedagogical content knowledge (ePCK) in relation to their students' metacognition development. The results include a discussion of how these chemistry instructors valued their students' metacognition, how they currently develop their students' metacognition, and their suggestions for improving the development of metacognition in undergraduate chemistry education. Based on the results of this analysis, activities that indirectly target students' metacognition may be more easily adopted by instructors, and more explicit awareness may be beneficial.

Introduction

Many instructors have had students come to them after an exam, baffled by how poorly they performed. Students in this situation frequently believe they studied as much as humanly possible; often studying for a long time without questioning how efficiently they study. Kruger and Dunning (1999) found that many low-scoring students lack an awareness of their level of competence in a variety of areas. From their results, Kruger and Dunning claimed that these “incompetent” students lacked the declarative knowledge—an aspect of metacognitive knowledge—to discern what material they did not understand. There is evidence of this Kruger-Dunning effect in chemistry education (Bell & Volckmann, 2011; Casselman & Atwood, 2017; Hawker et al., 2016; Mathabathe & Potgieter, 2014; Pazicni & Bauer, 2014; Rickey & Stacy, 2000). Because of this evidence of chemistry students also lacking an awareness of their knowledge, metacognition is a relevant concept to students learning chemistry. Additionally, the choices we make as instructors can guide students in developing their metacognition through metacognitive training activities (Casselman & Atwood, 2017).

Chemistry education researchers have found that low-scoring students tend to have a lower awareness of their knowledge, but they can improve their awareness with training. Pazicni and Bauer (2014) and Hawker et al. (2016) found that general chemistry students in the C-D grade range were much less accurate and more likely to overestimate their exam scores than students in the A-B grade range, who were more likely to underestimate their scores, and that students’ awareness of their knowledge was consistent throughout the semester. Casselman and Atwood (2017) found that with metacognitive training, students in the C-D range improved their ability to accurately predict their test scores and improved their test scores by 10% compared to a control section. Kelly (2014) also worked with general chemistry students, and in her study, which focused on these students’ understanding of molecular visualizations, she found that the students who lacked metacognitive skills had difficulty evaluating their own understanding. González and Paoloni (2015) found that students’ metacognitive strategies in problem-solving positively predicted students' performance in a chemistry course. Adadan (2020) found that preservice teachers with high metacognitive awareness outperformed preservice teachers with low metacognitive awareness after being instructed about gas behavior. Additionally, methods have been developed to characterize and measure students' metacognitive abilities (Cooper & Sandi-Urena, 2009; Sinapuelas & Stacy, 2015) and to inform students about metacognition or to promote students' metacognitive development (Blank, 2000; Cook et al., 2013; Graham et al., 2019; Mutambuki et al., 2020; Sandi-Urena et al., 2012; Swamy & Bartman, 2019; Thomas, 2017; Visser & Flynn, 2018; Yuriev et al., 2017).

This is only a sample of the many studies in chemistry education research (CER) that have focused on chemistry students' metacognition. Despite the research and data available about students, there is a gap in the literature of studies focused on chemistry instructors, and their perspectives of metacognition, or its importance and relevance in the undergraduate chemistry classroom. Beck and Blumer (2016) conducted a survey study of undergraduate biology laboratory instructors, in which one of their five constructs included metacognition. While not a focus of their study, they labeled three of their 30 items as involving metacognition (e.g. "I can describe what I was supposed to learn"). They found that students said they had these experiences more often in the course than the professors thought the students did. While developing a new problem-based laboratory curriculum, Sandi-Urena, Cooper, and Gatlin (2011) interviewed the teaching assistants (TA's) to understand their experience with the new curriculum. They found that the problem-based structure of the new curriculum encouraged the teaching assistants to think more creatively, and this helped the TA's to also be more creative in their research. The new curriculum also challenged the TA's previously held epistemologies, which Sandi-Urena and his team believed caused the TA's to have a metacognitive experience. From this, they concluded that the new curriculum not only benefited the graduate students by encouraging their creativity, but it also developed their metacognition. Often, chemistry instruction is not designed to develop students' metacognitive abilities (Thomas & Anderson, 2014). However, instructors have a large influence over what is presented in their courses and in turn learned by students. Since metacognitive skills may aid students in learning chemistry, and instructors' choices guide what is learned by students, it is important to understand instructors' perspectives on metacognition in their courses. To address the lack of research on instructors, we designed this study to explore chemistry instructors' perspectives of metacognition in their courses.

Theoretical Framework

Zohar and Dori's (2012) definition and description of metacognition framed this study. Metacognition is frequently described as "thinking about your thinking". In this framework, built upon prior work (i.e., Flavell, 1979; Schraw & Dennison, 1994), metacognition is differentiated into two main ways to think about thinking: knowledge of one's knowledge (metacognitive knowledge) and regulation of knowledge (metacognitive skills). Metacognitive knowledge has three main subtypes: declarative knowledge, procedural knowledge, and conditional knowledge. Metacognitive knowledge can be appropriately or inappropriately applied to a learning situation; just because a student has metacognitive knowledge does not mean it is accurate, or that they know how to apply it correctly (Veenman, 2012). Thus, it is important that students get many opportunities to practice their metacognition (Zohar, 2012).

Declarative knowledge is one's knowledge of what they know and what they do not know, for example when a student knows that they know the chemical formula of sodium hydroxide but not sodium nitrate. Procedural knowledge is knowledge of how to implement learning procedures and strategies, for example, knowing how to make flashcards, or how to organize notes in the most useful manner. Conditional knowledge is knowledge of when to implement learning strategies. For example, a student uses their conditional knowledge when they know that the best time to use flashcards is when they are trying to memorize lots of information, like the names and formulas of polyatomic ions, but that flashcards would not be appropriate for applying processes such as learning stoichiometry. Veenman (2012) discusses the importance of conditional knowledge for students who are developing metacognitive skills. Conditional knowledge is how students discern when and why a strategy should be applied and developing this knowledge on learning strategies is how students develop their metacognitive skillfulness. There are five types of metacognitive skills that regulate one's knowledge: planning, information management, monitoring, debugging, and evaluating. To explain these five regulatory skills, we will describe how a chemistry student could employ them while solving a stoichiometry problem. At the start of their work, a metacognitive student employs planning by thinking about what information was given to them in the problem, and what the problem wanted them to find: the gram amount produced of one of the products. The student then organizes the information provided according to a system that allows them to easily proceed with solving the problem—using their information management skill. Then while solving the problem a metacognitive student frequently checks to make sure they are working towards the goal they set while planning how to solve the problem—this checking during the task is metacognitive monitoring. While solving the problem, the metacognitive student may become aware of an issue: for example, they realize they forgot to balance the equation before beginning. Monitoring would alert them to the issue, and then the debugging skill would allow the student to solve the issue, by realizing they needed to return to the chemical equation and balance it, and then making any necessary changes to their calculations. Upon reaching a solution to the problem, a metacognitive student reflects on their work and their thought process—metacognitive evaluating.

In addition to theories on students' metacognition, the revised consensus model (RCM) of pedagogical content knowledge (PCK) framed our analysis into instructors' perspectives on metacognition in their courses (Carlson & Daehler, 2019). The revised consensus model is an elaboration and clarification of the consensus model (CM) (Gess-Newsome, 2015) and not a replacement of these models (Carlson & Daehler, 2019). The RCM differentiates levels of PCK: collective PCK (cPCK), personal PCK (pPCK), and enacted PCK (ePCK). The RCM brings clarification and benefits to theory on PCK, including a discussion on the intricate relationship between pPCK and ePCK—an instructor's personal knowledge, beliefs, and thoughts on teaching science and what practices they enact in their classroom (Hume et al., 2019). Carlson and Daehler (2019) describe the inter-relatedness of ePCK and pPCK:

> In the RCM, the knowledge exchange between ePCK and pPCK operates in both directions—the insight a teacher takes away from each interaction with students further informs the teacher's pPCK, and the ePCK a teacher brings into practice for a specific science learning moment depends on the teacher's specific knowledge and skill, which is

> amplified and filtered through pedagogical reasoning. As such, pPCK is both informed by and informs ePCK. (Carlson & Daehler, 2019, p. 86)

Measuring or observing ePCK is difficult because it would require an instructor to be able to narrate their thoughts while simultaneously teaching a lesson (Alonzo et al., 2019). Currently, the best methods of understanding ePCK also include understanding pPCK, because the two are so intertwined. This model allowed us to investigate what pPCK these instructors had relating to metacognition development for their students based on interviews on their teaching practices and their expectations of students in their course. By exploring the pPCK of these chemistry instructors, we can begin to comprehend their ePCK, which directly affects what happens in their classrooms.

Rationale for Study

According to the consensus model of teacher professional knowledge, (Gess-Newsome, 2015) an instructors' pedagogical content knowledge (PCK) and classroom practices may not perfectly reflect their knowledge of best teaching practices, because PCK and classroom practices are the result of the instructor's knowledge of teaching and topic-specific teaching practices after they have been filtered through the teacher's beliefs and orientations towards teaching. So even though an instructor may have knowledge of many useful forms of assessment, and the best way to assess a specific topic, if their beliefs about teaching do not align with that method of assessment, they are less likely to implement it. Teachers' orientations and beliefs about teaching also affect how they present material for their students to learn, and the skills they choose to attempt to develop in their students. Tepner and Sumfleth (2019) posit that teachers' perceptions, attitudes, and beliefs act as amplifiers and filters to PCK as implicitly represented within the RCM and should be more explicitly discussed because these filters have a "significant impact on teachers' enactment in classrooms and their students' learning achievement" (p. 326). In the RCM, a teacher's beliefs and attitudes towards teaching are wrapped up in their personal PCK (pPCK), which directly informs and affects their classroom practices, or their enacted PCK (ePCK) (Alonzo et al., 2019). Gess-Newsome et al. (2003) and Henderson et al. (2011) discuss the importance of teacher beliefs when instructors choose to enact new teaching practices. According to both, teachers will not seek out new teaching practices unless they feel dissatisfied with the current state of their pedagogy.

Since undergraduate instructors have a wide influence over what happens in their courses, it is crucial to investigate their understanding of metacognition, and discern whether they value metacognitive development for their students. Despite research in general chemistry courses and studies focusing on general chemistry students' metacognition, there is scant research on postsecondary chemistry instructors' perspectives of metacognition. We used interviews to gain a richer understanding of chemistry instructors' thoughts, perspectives, and pPCK about their students' metacognition development, while answering the following research questions:

Q1 In what ways do current postsecondary chemistry instructors value their students having metacognitive skills and knowledge?

Q2 How are current postsecondary chemistry instructors encouraging the development of metacognitive skills and knowledge in their students?

Q3 What are current postsecondary chemistry instructors' thoughts, suggestions, and strategies for improving metacognition in their students?

Methods

Participants

Seventeen instructors from six different schools across Colorado accepted an email invitation to participate in this interview study. (See table 4.1 for the demographics of the participants.) The instructors ranged from non-tenure track lecturers to fully tenured professors, ranged from having few years of experience to many (0-25+ years of experience), came from different institutional contexts (R1, R2, PUI), and discussed a range of classroom contexts (general chemistry, organic chemistry, or biochemistry). The email invitation asked instructors to choose an exam-type question from one of their courses to discuss in the interview. Participants were offered a gift card to thank them for their participation.

Table 4.1

Demographics of Instructor Participants

Demographics of instructor participants	
Course taught	**Number of participants**
General Chemistry	8
Organic Chemistry	6
Biochemistry	3
Years of Experience	**Number of Participants**
0-5	3
6-10	6
11-15	3
16-20	2
20-25	2
25+	1
Tenure Status	**Number of Participants**
Tenured	8
Tenure-track	4
Non-tenure track	5
Institution Type	**Number of Participants**
R1	7
R2	4
PUI	6

Data Collection

The interview protocol was designed so that the interviewer did not bring up the word “metacognition” or “metacognitive” until the last phase of the interview, in order to observe whether participants discussed metacognition without prompting. We did this to limit social desirability bias in participants' answers (i.e. instructors saying that they value developing their students’ metacognition just because the interviewer asked and not because it is something important to their course). Instead, by allowing instructors to talk about their course more generally and their expectations for students, we could identify if developing their students’ metacognition was important enough to talk about even when they were not explicitly asked to do so. The protocol was iteratively edited and reviewed after the first few interviews, and the final version of the protocol is in Appendix C. The interview moved through four phases.

In the first phase, the researcher asked questions to “warm up” the instructor being interviewed (i.e. “What course(s) do you currently teach?”, and “What do you want students to learn in this course?”). The second phase discussed an exam question and the interviewer asked the instructors to discuss the thought process of a proficient student as they solved the problem. The exam question gave a tangible object to reflect upon from their teaching in order to make it easier for the instructor to be specific while discussing their expectations and perspectives. In the third phase (implicit metacognition discussion), the interviewer asked the instructor to describe the habits and skills they would attribute to the “ideal student” for their class. Finally, in the fourth phase of the interview, the interviewer asked explicit questions about the instructors’ perspectives on metacognition (i.e. “What comes to mind when you think of the term metacognition?”, “Can you think of ways that you use metacognitive skills in your life—either at work or elsewhere?", and "Do you do anything to specifically develop metacognitive skills in your students?") If instructors were not familiar with metacognition, the interviewer briefly defined metacognition and provided examples.

The interviews were recorded and later transcribed verbatim, except for stammering phrases such as "um", which were removed for clarity. The interviews lasted from 30 minutes to 1 hour and 20 minutes. The interviewer also collected demographic data from the participants. All participants gave informed consent to participate in the study, and this study was approved by the Institutional Review Board of the University of Northern Colorado.

Data Analysis

After every interview the first author recorded her initial thoughts and observations from the interview. The transcripts were analyzed by reflexive thematic analysis (Braun & Clarke, 2006; Braun et al., 2019) in Nvivo 12 to define themes. In an iterative manner, we followed Braun et al.'s (2019) phases of 1) data familiarization, 2) generating codes, 3) constructing themes, 4) reviewing themes, and 5) defining themes. After every interview, initial thoughts and observations were recorded. Coding began by writing a summary of each codable instance. The codable instances were identified as the participant's response to each of the interviewer's questions. Specific codes were developed that closely matched the statements of the participant. Annotations in Nvivo 12 were used to capture the reasoning for assigning different codes to a quote (Merriam & Tisdell, 2016). When multiple related codes were identified, these codes were then grouped into major themes and previously coded transcripts were re-analyzed to catch all instances in the data set. Upon coding of all interviews, both authors individually re-reviewed and consolidated the codebook to arrive at the finalized codebook. The second author then coded four of the interviews for inter-rater agreement and met with the first author to review any disagreements in coding. Initially there was disagreement in 20% of the codes, which were discussed, and agreement was reached on each of these codes.

Our analysis included both deductive and inductive processes. Zohar and Dori's (2012) framework of metacognition informed coding of the interview transcripts, so that they were coded for instances of instructors talking about students' metacognitive knowledge and metacognitive skills during all parts of the interview. In order to focus the analysis on portions of the transcripts that discussed metacognition, in our deductive analysis, the authors coded for any instances where the instructors' discussion of their students, or their own teaching practices and learning experiences were examples of one or more of the subnodes of metacognitive knowledge (declarative knowledge, procedural knowledge, and conditional knowledge) or metacognitive skills (planning, information management, monitoring, debugging, and evaluating). Because of the organization of the interview guide, many of these instances of metacognition were not identified as such by the instructors, since the questions prompting their discussion in the first three sections of the interview purposefully were not explicitly asking about metacognition. The interviews were then coded inductively to describe the ways instructors value and develop their students' metacognition and their suggestions and strategies for improving metacognition in their students. We then related these results to the RCM of PCK (Hume et al., 2019). These inductive codes described these instructors' pPCK of their students' metacognition development.

Results and Discussion

From analysis of these interviews, we identified aspects of these instructors' pPCK about their students' metacognition, which was interwoven with their beliefs and their ePCK. As instructors reflected on their teaching practices, we were given a glimpse into their ePCK (Carlson & Daehler, 2019). We uncovered how these instructors valued metacognition, how they described their current metacognitive development practices, and suggestions they had for their students' metacognitive development. Our initial deductive analysis, framed by Zohar and Dori's (2012) description of metacognition, identified that all the types of metacognitive knowledge and metacognitive skills were discussed by these instructors, though all types were not present in every interview. Every interview was coded with some type of metacognitive knowledge and metacognitive skills. Table 4.2 provides the definitions of the different types of metacognition according to Zohar and Dori (2012), example quotations from this study's data set, and an explanation for why that code applied to the quote.

Table 4.2

Deductive coding scheme. Type and definition of metacognition according to Zohar and Dori (2012).

Metacognitive Knowledge	
Example quote	**Explanation**
Declarative knowledge: "Knowledge about one's skills, intellectual resources, and abilities as a learner"	
"Well, in some cases I've seen that they are overconfident with some concepts that say, for example, and this happens when you go to office hours after the exam, and they say, 'Oh I studied so hard and I failed the exam. I don't know what happened.'" Felipe, lines 212-214	Felipe describes students who lack declarative knowledge, because they were unaware of what concepts they did not know
Conditional knowledge: "Knowledge about when and why to use learning procedures"	
"Or maybe previous experiences, if they are re-taking the class, sometimes it has flipped, they have flipped their mindset and they are doing something totally different to be successful or they have found, 'oh, what I did was that, was not correct or not helpful, then let me change that strategy to you know, actually pass the class.'" Felipe, lines 252-256	Felipe discusses how students who are re-taking a class may have developed their conditional knowledge, they now are able to identify what learning strategies are most appropriate to employ for them to pass the class.
Procedural knowledge: "Knowledge about how to implement learning procedures (e.g., strategies)"	
"But for me, I guess if I don't understand something, I keep working at it until I do. And I do just basically this; I'd draw pictures of the things, I think about trying different things, but I just keep trying different things until I get the right solution. But then I go back and I try to think, 'Well why did I make the wrong solution to begin with?'" Truong, lines 270-273	Truong describes a learning procedure he implements when trying to understand something new: drawing pictures, trying different things to get to the solution.
Metacognitive Skills	
Planning: "Planning, goal setting, and allocating resources prior to learning"	
"I mean planning how to teach a course. First you have to decide...first you have to learn the material, then you have to decide what's important to teach and then you have to decide how you're going to deliver it, and then how you're going to test people on it. What is it I actually want people to know and what are ways I can assess that?" Noam, lines 225-228	In this quote, Noam describes how he uses metacognitive planning to organize the materials he needs to cover (allocating resources) and sets goals for how to successfully teach students the learning objectives of the course.

Table 4.2, continued

Metacognitive Skills	
Example quote	**Explanation**
Information Management: "Skills and strategy sequences used on-line to process information more efficiently"	
"Color coding, different color paper, different flags, everything, I think those are amazing, I always have flags for everything. And I tried to highlight and underline things so that I could remember." Felipe, lines 336-338	In this quote, Felipe describes how he uses the strategy of color-coding information to help him process and remember material more efficiently.
Monitoring: "Ongoing appraisal of one's learning or strategy use"	
"when I attack a problem, usually not Gen Chem problems, but sometimes, I'll start it and I'll be like, 'Oh, work it out this way,' and then I'll realize halfway through I'm making a bad assumption and then I'll have to re-work it. And that's just how it goes." Janay, lines 61-64	In this quote, Janay describes how in the middle of working on a problem, her monitoring skill alerts her to when she has made a bad assumption, and that she needs to re-start the problem.
Debugging: "Strategies used during learning to correct comprehension and performance errors"	
"So what I started telling my students at the end of this last semester was, when you have a problem…write a sentence about the problem that tells—that says, 'This problem is asking this. I solved it by identifying blah blah blah,' and then writing just a para—a little two- or three-sentence description of how you solved the problem. Especially do this when you run into a problem halfway through. So, like, and if you do, describe what you ran into, and why, and how you solved that." Janay, lines 440-446	In this quote, Janay describes how she teaches her students to metacognitively debug: when they run into a problem, they should write a sentence or two describing what they did and why they did it, which causes the students to evaluate their thinking process in solving the problem, and allows them to look for performance errors.
Evaluation: "Analysis of performance and strategy effectiveness after a learning episode"	
"I mean we do, kind of, the one-minute papers occasionally in class, so like, 'what do you really understand? What don't you understand? What one thing would you change about what we've been doing?'" Ming, lines 377-379	At the end of a lecture, Ming likes to use one-minute papers to allow her students to evaluate their understanding of the material they learned during that day's class period.

The metacognitive skill “evaluation” was present in sixteen of the interviews, which was the highest frequency for any of the types of metacognition. The least coded type of metacognition was the metacognitive skill “monitoring” which was only coded in four of the interviews. Because “monitoring” is a skill that happens during a task, the authors were not surprised that discussion of this skill was scarce. Even though the instructors were not explicitly asked about metacognition until the last section of the interview guide, all seventeen instructors discussed something metacognitive before the explicit metacognition discussion portion of the interview. Thus, the interview guide was successful in implicitly and explicitly prompting instructors to discuss students’ metacognition in the context of their course. We will now discuss the results of our inductive analysis of how these instructors valued metacognition, how they described their current metacognitive development practices, and suggestions they had for their students’ metacognitive development. Table 4.3 provides the inductive codes (names and descriptions) found in the data.

Table 4.3

Inductive codes names and definitions

How instructors value metacognition: Level of importance of metacognition (I1)	
I1a: Metacognition not valued	*Instructor did not value metacognition*
I1b: Metacognition is not crucial, but could be important	*Instructor made statements indicating that metacognition was not essential for their students, but that it could be useful or important*
I1c: Metacognition development is more important than chemistry	*Instructor made comments that indicated they believed developing their students' metacognition was more important than teaching them about chemistry*
How instructors value metacognition: Who's responsible for students' metacognition (I2)	
I2a: student responsible	*Instructor believed only the student is responsible for developing their metacognition*
I2b: another course responsible	*Instructor believed another course is responsible for developing metacognition*
I2c: instructor responsible	*Instructor believed they are responsible for developing their students' metacognition*
How instructors value metacognition: Why instructor thinks metacognition is important (I3)	
I3a: Metacognition leads to success	*Instructor believed metacognition will help students be successful in the future*
I3b: Value in metacognition inside and outside the classroom	*Instructor discussed instances of the importance of metacognition inside and outside of the classroom*
I3c: Important for students to know how they think	*Instructor believed students should use metacognition, including when they think about how they think about chemistry*

Table 4.3, continued

How instructors value metacognition: How natural is metacognition (I4)	
I4a: Develops naturally	*Instructor believed students' metacognition develops without prompting, innate skill*
I4b: Does not develop naturally	*Instructor believed students' metacognition does not develop without training*
I4c: Natural to not think about thinking	*Instructor believed metacognition is unnatural*
How instructors value metacognition: Types of metacognition valued by instructors (I5)	
I5a: Values metacognitive knowledge	*Instructor made statements indicating they value students having strong declarative knowledge, procedural knowledge, and/or conditional knowledge*
I5b: Values metacognitive skills	*Instructor made statements indicating they value students having strong planning skills, information management skills, monitoring skills, debugging skills, and/or evaluating skills*
How instructors value metacognition: Values metacognition without knowing definition (I6)	
I6: Values metacognition without knowing definition	*Instructor assigned value to some activity or habit that the researchers coded as metacognitive, though the instructor could not define or describe "metacognition"*
Developing metacognition in students (I7)	
I7a: Explicit metacognition development	*Instructor explicitly discusses with students the importance of metacognition, by using the terms "metacognition" or "metacognitive"*
I7b: Implicit metacognition development	*Instructor discusses the importance of metacognition with their students, but does not use the term "metacognition", and does not provide activities or assignments for the students to practice using their metacognition*
I7c: Implicit metacognition development with scaffolding	*Instructor discusses the importance of metacognition with their students without using "metacognition" or similar terms, and described a scaffolded activity or assignment they provided students to practice using their metacognition*

Table 4.3, continued

Suggestions for metacognition development (I8)	
I8a: General suggestions	*Suggestions made by instructors that allude to generic teaching practices, and do not mention specific steps with the goal of developing student's metacognition*
I8b: Metacognition-specific suggestions	*Suggestions made by instructors that mention specific steps with the goal of developing student's metacognition*
Barriers to metacognition development (I9)	
I9a: Institutional barriers	*Barriers related to the institution, or just to the nature of teaching at a university*
I9b: Student barriers	*Barriers related to the students*
I9c: Instructor barriers	*Instructors identified ways that instructors (themselves and other colleagues) can be barriers to their students' metacognition development*
I9d: Time barriers	*Instructor identified that they don't have the time to learn about metacognition to be able to teach it, or don't have the time to implement it in class.*
Instructors mistaking cognition for metacognition (I10)	
I10a: Reflection is metacognition	*Instructor discussed a reflection activity but did not discuss that the students are reflecting on their thinking processes in some way*
I10b: Thinking deeply is metacognition	*Instructor identified activities/questions/homework that "really makes them think"*
I10c: Review sessions develop metacognition	*Instructor discussed review sessions but did not discuss any activities in those workshops/review sessions that encourage students to think about their thinking*

How Instructors Value Metacognition

There was one overarching code that answered the first RQ: "In what ways do current postsecondary chemistry instructors value their students having metacognitive skills?" which was named "How instructors value metacognition".

Level of Importance (I1)

This first subnode of how these instructors valued metacognition included instances where instructors discussed how important developing their students' metacognition was in their class. There were instructors in this study that either did not value metacognition, believed it was important but not crucial, or believed it is more important than teaching students chemistry.

Metacognition Not Valued (I1a). Of the seventeen instructors interviewed, there were two that did not think metacognition was important for their class. Hector, (PMC1-14), did not believe metacognition was necessary or helpful for his students' success:

> Researcher: Would you say, so would you say that it's any person's responsibility to teach students about metacognition? Like your responsibility, or a previous instructor in their life? or not?
>
> Hector: No, I don't think that.
>
> Researcher: No? Ok. Why not?
>
> Hector: That's good question, why not? Because I think a good teacher, when he teach you, everything's comes very naturally. You don't really need to be aware, there is something behind this, like a formal organization, a formal way of doing the things. When a good teacher teach you, everything just come like water flowing through. So

> natural. You aren't aware of anything and you already learned it. Does that make sense? (Hector, lines 254-263)

According to Hector, it is better for his students to not think about how they think about things, and he believes it is a sign of good teaching when a student is able to absorb knowledge without being aware that they are learning.

Metacognition is Not Crucial but Could Be Important(I1b). There were six instructors that made comments about metacognition that indicated they believe it is not essential for their class but could be important for students. Kichion, was one of those instructors:

> Researcher: Do you feel that it's your responsibility to teach them [students] how to use metacognitive skills?
>
> Kichion: I think it's important skill, but I do what I can, but I don't consider that to be my primary responsibility, I think this would be a good topic to cover in maybe University 101, just to get them ready for college…I think it is, I think it is important. I mean it's just not for this class, I think, it's probably a life skill as well. But yeah, I definitely say it is important. But I just don't have, like I cannot devote a whole lot of, you know, the class time, to that. (Kichion, lines 356-360, 371-373)

Like Kichion, other instructors could see the value of their students being metacognitive but were concerned that their current curriculum did not have time available to spend on teaching students about metacognition or doing in-class activities to develop metacognition. Instead, some instructors considered resources outside of their course, such as courses designed to teach study skills, as a place for students to learn metacognitive skills.

Metacognition Development is More Important Than Chemistry (I1c). There was one instructor, Isaac, who believed that metacognition development was more important for his students than teaching them about chemistry.

> Isaac: And so that, the entire point of that simulation was a basically a metacognition experiment. I mean I think that probably a number of the students did learn, actually I know because I evaluated it, that a number of students did learn a fair bit about, you know, the topic at hand, you know, being able to express and purify proteins. But I think that that was the less important lesson. (Isaac, lines 398-402)

To Isaac, learning all the small details about chemistry was not necessary for his students to be successful. He believed that teaching in a manner that allowed students to think about how they think about chemistry and research is what is necessary for his students to be successful chemists. There were also nine instructors who did not indicate during their interviews how important metacognition was for their students, simply that they believed it was important.

Who's Responsible (I2)

Besides discussing how important metacognition development is in their classes, when asked, instructors also discussed who they believed was responsible for developing students' metacognition. There were three main groups of beliefs about "who's responsible". Some of the instructors (3 instructors) believed metacognition was fully the students' responsibility to develop on their own. Others (3 instructors) believed they could spend some time discussing metacognition with their students and provide them with a few resources for developing their metacognition, but they thought it would be preferable for their students to develop metacognition elsewhere, such as in a study skills class. The last group (9 instructors) believed that developing their students' metacognition was the instructor's responsibility, and three of these believed metacognition was so important that it should be incorporated into every class their students take—one instructor even believed metacognitive training should begin as early as elementary school for students.

Why Instructors Think Metacognition is Important (I3)

One reason why instructors regarded metacognition as important for their students was because it would help them to be successful in college, and later in life. Natalia, in the quote below, is an example of one of the instructors who discussed how she believed metacognition leads to success for her students:

> We try to say in class, 'This is the reason that we're doing this. We're doing this because it's really important for you to think about how you're thinking about things. And this will help you to be more successful in our class and other classes as well.' (Natalia, lines 606-609)

Natalia believes metacognition is beneficial for her students, and that metacognitive skills will help them to succeed in her class and other classes they will take in their undergraduate career. There were four instructors in this study who believed metacognition would be valuable for their students beyond the chemistry classroom. These instructors discussed how they believed metacognition was not only helpful for their students in learning chemistry, but that it would also help them in their future careers. One example of this is Felipe:

> Researcher: So do you think metacognition is important for your students?
>
> Felipe: Absolutely, yeah. Absolutely, 'cause, it is not only important for the classes, this is a skill that I think that they will carry for the rest of their careers, as they go to any job,

> and they need to solve problems all the time. And if they're in the sciences that's what they are gonna do, so I think that metacognition is part of being in the sciences. (Felipe, lines 434-438)

Felipe discusses how he believes metacognition is important for his students in his class, but that is not the only reason metacognitive training could be beneficial for his students—he also believes that having strong metacognition will benefit his students in the future. His comment "metacognition is part of being in the sciences" conveys just how necessary Felipe believes metacognition is for his chemistry students.

How Natural is Metacognition? (I4)

There were three instructors that discussed how natural they believed metacognition and metacognitive skills to be, and they all held contrasting views. As we saw in George's earlier quote, he believed that he did not need to train his students how to be metacognitive, because "if you're motivated to succeed, you're gonna figure it out," (George, line 249). Rinchen believed the opposite was true for students, that without metacognitive development or training his students were unlikely to use their metacognitive knowledge and metacognitive skills. Rinchen said, "We found that college freshmen engage in very little metacognition" (Rinchen, line 124). The last instructor that discussed how natural metacognition is was Hector. As we saw in his earlier quote, Hector believed that it is natural to not think about your thinking, or that metacognition is not natural. Hector said, "When a good teacher teaches you, everything just comes like water flowing through. So natural. You aren't aware of anything and you already learned it." (Hector member check, lines 24-26) There was no specific question in the interview guide that addressed the idea of "how natural is metacognition for students?", so it is understandable that such a small number of instructors discussed this idea.

Types of Metacognition Valued by Instructors (I5)

Many of the instructors made statements that indicated they valued metacognitive knowledge and metacognitive skills. Rarely did instructors use the terms "metacognition" or "metacognitive", but questions in the interview elicited their views on student study skills and habits. The researchers coded for instances of metacognitive knowledge and metacognitive skills, but also coded for when instructors specifically indicated that some type of metacognitive knowledge or metacognitive skill was beneficial to their students. There were twelve instructors that made comments throughout their interviews that indicated they valued their students using some type of metacognitive knowledge, either conditional knowledge, procedural knowledge, or declarative knowledge. There were eleven instructors that valued their students' metacognitive skills, and the most coded metacognitive skill was "instructor values students being able to self-evaluate".

Values Metacognition Without Knowing the Definition (I6)

The last subnode that described how instructors valued metacognition was "values metacognition without knowing the definition". This was coded in interviews when in the first three phases of the interview (prior to an explicit question about metacognition) some instructors made statements indicating they valued some type of metacognition. However, later in the interview these instructors responded to the question "What comes to mind when you think of metacognition?" by saying they did not know what metacognition was, or that they had heard of the word, but nothing immediately came to mind describing metacognition. Thus, this code was only applied to quotes from the first three sections of the interview guide, before there was any mention of metacognition made by the interviewer. An example of an instructor valuing metacognition without knowing the definition can be seen from Rob's interview:

> But I think a very important skill that I learned from my experience, now I'm teaching my students as well, we have to learn the way to study. So it is not just about how many hours we spend on the materials, but also the proper way of study, am I efficient in going through the materials? Do I have the correct way of doing the questions? And do I ask the proper questions to my instructors, or to my tutor? When do I seek help? Do I seek help right away, you know, before I even look at a question I ask somebody to help me solve it? Do I try solving the problem, then I fail, then ask people to give me suggestions or hint? So I think those are more important skill and learn how to study, I think is, especially for organic chemistry. (Rob, 283-291)

Rob wants his students to learn how to learn in his class. He believes that if his students can properly evaluate their current learning procedures (metacognitive skills, evaluating) that they will be able to develop better metacognitive knowledge of how to learn (metacognitive knowledge, procedural knowledge). From this quote, it is obvious that Rob values metacognition, even though later in the interview he is not familiar enough with the term to describe it.

Current Metacognitive Development Practices

The second research question of this study, "How are these instructors encouraging the development of metacognitive skills in their students?", was addressed in another of the top-level nodes in the codebook: "Developing metacognition and learning strategies". There were three main approaches to metacognition development discussed by the instructors in this study: explicit metacognition development, implicit metacognition development, and implicit metacognition development with scaffolding.

Explicit Metacognition Development (I7a)

Explicit metacognition development was found in one interview, when an instructor said he explicitly discussed the importance of metacognition with his students, using the terms "metacognition" and "metacognitive" in his class.

> I think that, and I tell my students from day one, you need to be familiar with a metacognitive approach. Metacognitive approaches to studying, how to study, and learning how you are learning, is probably one of the most important things in self-diagnosing for correcting when you have a insufficiency or some kind of cognitive disconnect. Because if you understand, or if you can recognize that when you answer a question, you're not doing that at 100% confidence, that you're not really sure of what the answer is, but you got it right, and then you say, you just decide, 'Oh ok I guess that's ok.' That that can be just as lethal for your grade as being outright wrong, because at least if you're outright incorrect you know, 'I didn't know the material.' But if you do that with false self-confidence, and you think you know the material, that's just as bad. (Kevin, lines 350-359)

Kevin discusses with his students why he thinks metacognition is so important for them, that he believes it is crucial for his students to have a metacognitive approach to studying. Kevin believes that it is important for students to have strong declarative knowledge, so that they can be aware of when they know something and when they do not know something as well as they should. In his interview, Kevin did not discuss any class activities that he implements to provide practice for his students to develop their declarative knowledge, he only described how he frequently tells his students about the importance of metacognition in their studying. All other instances of metacognition development in this interview study were coded as either implicit development, or implicit with scaffolding.

Implicit Metacognition Development (I7b)

The researchers defined implicit metacognition development as instances where the instructor discusses the importance of doing things that the researchers coded as metacognitive, but the instructor does not use the terms “metacognition” or “metacognitive” with their students. In un-scaffolded instances, the instructor encourages their students to do these things, or to develop certain skills, but does not provide any sort of activity for the students to practice the skills or habits the instructor says is important. An example of implicit metacognition (un-scaffolded) development can be seen in Kaili’s interview:

> ...it's talking to them about, ‘How do you know what you know?’ and I, I do tell them it's part of the soft skills of a class. Do I assess it, whether they have metacognition? No. I tell them, ‘You need to do this in your life, but I'm not going to take points off because you haven't been able to,’ but I could. I think, maybe give some points for starting to think about those things. (Kaili, lines 274-282, 656-659)

Kaili frequently emphasizes the importance of “knowing what you know” to her students, which is declarative knowledge, but does not provide any activity for her students to practice evaluating the limits of their knowledge. She admits that she views metacognition development as an important “soft skill” but does not consider it to be important enough to give students credit for working on being more metacognitive in her class. Earlier in her interview, Kaili mentions that she likes test questions that require students to integrate a lot of knowledge, because they require students to reflect on what they need to know (metacognition). Even though she believes these types of questions should make her students pause and reflect on their understanding, she does not incorporate that reflection into the question, or in a homework or in-class assignment.

Implicit Metacognition Development with Scaffolding (I7c)

The difference between the definitions of “implicit metacognition development” and “implicit metacognition development with scaffolding” is that development with scaffolding includes activities for students to practice using their metacognition. “Implicit metacognition development with scaffolding” is still labeled as “implicit” because the instructor does not use the terms “metacognition” or “metacognitive” when discussing the importance of tasks that can develop students’ metacognitive knowledge and/or metacognitive skills, or when describing the activities they provide for students to practice using their metacognition. An example of an instructor implementing “implicit metacognition development with scaffolding” can be seen in Mar’s interview, as she discusses an activity that teaches her students how to evaluate their understanding:

> They have to actually take their problem set and the key and analyze it, and actually go through and say what was wrong about their answer, and then the most important, why is it wrong, you can't just say ‘I had the group on the wrong spot.’ You have to say well

> why is that the wrong spot? You know, what concept do you need to work on? (Mar, 214-218)

In this quote, Mar discusses the post-exam self-reflection assignments she has her students do after every exam. This assignment requires students to go over every incorrect answer and evaluate their thinking processes. Mar does not let students write simple short reflections about their answers either; they must fully explain why their thinking about the question was wrong and identify areas of study for them to improve. This activity requires students to practice the metacognitive skill of evaluating, and develop their declarative knowledge, specifically their knowledge of what they do not yet know.

Suggestions for Metacognitive Development

The last research question, “What are these instructors’ thoughts, suggestions, and strategies for improving metacognition in their students?” was answered by instructors’ responses to one of the later interview questions: “How can chemistry instructors as a whole improve the development of our students’ metacognition?” Instructors’ responses to this question varied, and the researchers categorized the answers into two main groups: general suggestions (7 instructors) and metacognition-specific suggestions (4 instructors).

General Suggestions (I8a)

Participants provided ideas that would be general improvements to teaching a course, suggestions that are considered good teaching practices, but that did not necessarily focus on metacognition development. Examples of general suggestions were implementing active learning practices, encouraging students to do lots of practice problems, and have students solve questions that encourage their evidence-based reasoning. The instructors with these more “general” responses conveyed the belief that if an instructor practiced good teaching practices, then students would naturally be metacognitive. The findings of Stanton et al. (2015), Pazicni and Bauer (2014), and Hawker et al., (2016) contradict this belief that students will become metacognitive without any prompting or training.

Metacognition-Specific Suggestions (I8b)

The metacognition-specific group was made up of only 4 of the instructors interviewed. These suggestions were focused on ways to incorporate metacognition development into a course. They included ways for instructors to improve, either by attending professional development or training sessions, by staying up to date with relevant chemistry education research literature, or by discussing the difficulties of teaching students about their metacognition with other instructors. Another instructor suggested the importance of incorporating metacognition development into the course by including it in in-class activities, homework assignments, and assessments. As Cooper (2015) discusses, students value what we assess and allot points to in a class, so incorporating metacognition development into course assignments could be a way to indicate to students the importance of metacognition.

Barriers to Metacognition Development

To fully answer RQ3, it is pertinent to also discuss the barriers to metacognition development these instructors were experiencing, because in order to make improvements, it is necessary to identify obstacles that may impede that improvement. The instructors we interviewed discussed four types of barriers they experienced to implementing metacognition development in their class: *institutional barriers, student barriers, instructor barriers, and time* *barriers*. Examples of *institutional barriers (I9a)* were the perception of class sizes being too large to implement metacognition development, that these instructors were not incentivized by their school or department to spend class time on "soft skills" like metacognition, and that while in graduate school, these instructors did not attend universities that prioritized training their graduate students how to teach chemistry. There was one instructor (Isaac) that mentioned he had not experienced any sort of institutional barriers, and throughout his interview he discussed multiple ways he was able to implement metacognition development in his classes. The researchers found this to be incredibly important—the only participant that could not cite any institutional barriers, described multiple activities he used in the classroom to develop his students' metacognition. The second type of barrier, *students as barrier (I9b)*, was discussed the most (9 instructors) of all the types of barriers. The main complaint voiced by instructors was that if they tried to implement any sort of metacognition development, students would not see the value in it, and would think the instructor was wasting valuable class time. In contrast, there were multiple ways our participants perceived *instructors as barriers (I9c)* to metacognition development. One belief was that instructors lack training to implement metacognition development, or simply do not know how to incorporate metacognition into their class in a meaningful way. Another belief was that chemistry is too abstract of a subject for metacognition to be relevant. Lastly, there were two instructors that believed that instructors do not value metacognition and are reluctant to self-evaluate their own teaching practices. The last barrier these instructors discussed is a common one whenever any change is suggested—there is simply not enough time (*time barriers, I9d*). There were multiple instructors that believed metacognition was important and valuable for their students but did not feel they had enough class time to spend on any sort of metacognitive development.

Mistaking Cognitive Development for Metacognitive Development (I10)

In the last portion of the interview guide, where metacognition was explicitly discussed, we observed several instances of instructors discussing ideas for metacognition development that, from what they said in that moment, did not demonstrate evidence of being metacognitive. When asked to describe activities that develop their students' metacognition, many instructors answered similarly to Isaac, who said he liked to use test questions that had students learn while taking the exam:

> Researcher: Is there anything else besides what we've discussed that you do to develop metacognition?
>
> Isaac: Oh, yeah so I mean, that's definitely one, that I would say, as well. And also, you know, the design an experiment types of exam questions. I've always liked exam questions where the, you learn something by taking the exam. Because students remember exams, more so than they're probably gonna remember anything that happened in the lecture. So if you can get them to learn something in the exam, then they've learned something and that's the point of the class. And so I like questions where they can still learn something on the exam. And designing experiments is one way to help do that. (Isaac, lines 469-477)

Isaac identified these "design an experiment" type test questions as an activity that can develop metacognition, but from this quote there is no evidence of how this activity encourages students to be metacognitive. Instead, students need to think deeply about what they know about experimental procedures. There may be aspects of this type of question that do encourage students to be metacognitive, but from what Isaac has said about the question in this quote, the researchers could not find any evidence of metacognition, only cognition. We also encountered this issue when some of the instructors discussed review sessions they held as ways to develop metacognition. For example, in Mar's interview she responds to this same question by discussing "special topic workshops" that she holds for students, but in her discussion she does not describe anything codable as metacognition. Similar to the test questions Isaac described, there could be metacognitive training and development happening in Mar's "special topic workshops", but from the information she provides about these workshops in her interview, the researchers were unable to code any type of metacognition. The last common example of instructors mistaking cognition for metacognition was the idea that if students are reflecting on something, they are using their metacognition. In his interview, Felipe discussed a reading reflection activity that he identified as metacognitive development, but his description does not specify what the students are reflecting on. If they just take time to absorb the information in the reading, or decide if the reading was interesting or not, that type of reflection is not metacognitive. The students could be reflecting on how well they understand the material after reading it (evaluating their declarative knowledge, which would be metacognitive reflection), but with the information provided here the researchers did not feel comfortable inferring that.

The researchers saw evidence of this code, "mistaking cognition for metacognition" even in the suggestions for metacognition development discussed above. Some of the ideas instructors suggested were viable options for encouraging students' metacognition, like Felipe's idea to incorporate metacognitive activities into assignments in the course. But other ideas the instructors presented lacked clear evidence of how that activity related to students' metacognition, such as the suggestions that students need to do a lot of repetitive practice, or need to answer questions that require them to build evidence-based arguments. What was intriguing was that the instructor's level of prior knowledge of metacognition did not relate to whether or not they made statements where they mistook metacognition for cognition; instructors who were able to perfectly define metacognition during the explicit metacognition discussion were some of the same people to suggest activities for metacognitive development that were not metacognitive in nature. This may have been caused by the wording of the questions in the interview guide. When the researcher asked participants about how they developed their students' metacognition, she did not ask the instructor to explain why they thought that activity would cause the students to be metacognitive. The researchers can only interpret what the instructors discussed, thus in instances where instructors only mention the cognitive aspects of an activity, the researchers concluded that the cognitive aspects were what the instructors believed were most relevant.

Contextual Features

According to the revised consensus model of pedagogical content knowledge, the learning context and broader contextual features such as teacher experience and school characteristics influence instructors' PCK (Carlson & Daehler, 2019; Wilson et al., 2019).

Type of Course

There were different learning contexts within this study in terms of the specific course the instructor decided to discuss: general, organic, or biochemistry. Overall, most codes occurred roughly equally between participants who were discussing these different courses. However, there were a few interesting features related to the type of course the instructors had selected to discuss. The instructor who indicated that developing students' metacognition was more important than chemistry had selected a graduate level biochemistry course to discuss. General chemistry instructors were the main participants to talk about *why* metacognition was important. Only general chemistry instructors gave thorough definitions of metacognition. Scaffolding when implicitly developing their students' metacognition was mainly discussed by general chemistry instructors. Time as a barrier was discussed mainly by instructors who selected their general chemistry course as the context of the interview. All of the instructors who selected biochemistry as the course for the context of the interview mentioned students as a barrier. From observing these trends in coding related to which course the instructor taught, we concluded that the general chemistry instructors in this study knew more about metacognition, why it is important for their students, and how to implement metacognition development in their courses. General chemistry instructors may be more knowledgeable about metacognition because of the larger proportion of research on metacognition development that has been conducted specifically in the general chemistry context.

Years of Experience

In this study there were roughly equal numbers of participants with ten or less years of experience (9 participants) as 11 or more years of experience (8 participants). Overall, most codes occurred roughly equally between participants with less and more years of experience. However, there were a few interesting features related to the instructors' years of experience.

Descriptions of how instructors developed their students' metacognition (explicit, implicit, or implicit with scaffolding) occurred more with instructors with fewer years of experience than instructors with more years of experience. The instructor who indicated that developing students' metacognition was more important than chemistry had fewer years of experience. Only instructors with more years of experience talked about how (un)natural metacognition was. The two instructors who stated that they did not value metacognition both had more years of experience. The professors who did not know about metacognition were only instructors with more years of experience. Discussions of institutional barriers and faculty as barriers occurred mainly by tenured instructors, whereas non-tenured instructors only talked about time and students as barriers. From these observations, we concluded that the more experienced instructors in this study did not know as much about metacognition, did not value metacognition as highly, and did less to develop metacognition than the instructors with less years of experience.

Institution Type

Overall, most codes occurred roughly equally between participants from different types of institutions (PUI, R1, R2). However, there were a few interesting features related to the instructors' institution type. Instructors coming from R1 institutions made up the majority of the instructors who talked about wanting metacognition development of their students to occur mainly in another course. However, instructors from R1 institutions were the only instructors to mention wanting to improve their ability to develop their students' metacognition.

Relationships Between Instructors' Values and Strategies to Develop Students' Metacognition

The two instructors (Truong and George) who did not talk about activities that could develop their students' metacognition also viewed the development of students' metacognition as the student's responsibility. However, they both made statements indicating that they valued something that could be defined as students' metacognition. For example,

> 'Each of you need to learn yourselves how you think best.' I said, 'Not all of you think the same, but that's your job to think—to learn how you think, because that'll only help you later on. If you know that way, people can maybe help you reinforce how you think, but the ultimate goal is you guys have to do it yourself.' (Truong, lines 424-428)

For Truong, it was important that students think about their thinking because this would help them later in their career, but he saw it was mainly the students' responsibility to figure out how to do that. Instructors who used scaffolding to develop their students' metacognition unsurprisingly also talked about metacognition as important for their class. Additionally, they made most of the comments detailing *why* metacognition is important. They were the only participants to talk about wanting to improve their teaching of metacognition. However, some instructors (3) who talked about scaffolded activities also thought it would be better if the students learned how to develop their metacognition in another course. For example,

> I think it's important skill, but I do what I can, but I don't consider that to be my primary responsibility, I think this would be a good topic to cover in maybe University 101, just to get them ready for college. […] it's probably a life skill as well […] I just don't have, like I cannot devote a whole lot of, you know, the class time to that. (Kichion, lines 357-371)

> For the last couple of semesters after the first exam, I give them a bonus assignment asking them to be self-reflective, how did you do on this test? What did you do to prepare for this test? Did it work? or did it not work? If it's not working, what do you plan to do differently? […] for the second test [...] did you use the strategy or whatever change you think you're gonna make after the first test? Did you do that? If you did, did it work? (Kichion, lines 321-334)

Kichion described a set of scaffolded activities he used in his class to develop students' metacognition (which he valued as an important life skill), but he felt time was limited for these activities within his course and saw value in this development occurring mainly in another course. Instructors who thought that metacognition development was the professors' responsibility were the instructors who talked about activities they used that could develop students' metacognition (explicitly, implicitly, or with scaffolding). Also, most instructors who valued metacognitive knowledge and skills discussed activities they implemented that could develop their students' metacognition.

Relationships Between Level of Knowledge About Metacognition and Strategies to Develop Students' Metacognition

The three instructors who were able to define metacognition all discussed ways they implemented metacognition development with scaffolding. Five of the six instructors in the knowledge category of "knew of metacognition but could not define" were already implementing implicit metacognition development with scaffolding, according to their descriptions of their classroom practices. All of the instructors that fully or partially defined metacognition discussed ways they were already developing their students' metacognition. The three instructors who were unable to define metacognition were split among different development groups. This led us to conclude that lacking knowledge about the definition of metacognition did not necessarily prevent these instructors from implementing it in their courses and encouraging it in their students, but that the instructors who were knowledgeable of metacognition could also discuss ways they implement it.

Relationships Between Types of Metacognition Discussed, Instructors' Level of Knowledge, Values, and Strategies to Develop Students' Metacognition

Every interview had some type of metacognitive knowledge and metacognitive skill coded. There were instructors from every knowledge level that were coded with discussing the different types of students' metacognitive knowledge: procedural knowledge, declarative knowledge, and conditional knowledge. For metacognitive skills, planning, debugging, and evaluation were present in interviews from all knowledge levels. Information management and monitoring were not present in interviews where the instructor did not know of metacognition but were coded in interviews from all other knowledge levels. Instructors from every knowledge level of metacognition valued metacognitive skills, especially the skill "evaluation". Additionally, all instances of valuing students' metacognitive knowledge were spread across all knowledge levels of metacognition. Thus, having a robust knowledge of metacognition was not necessary for these instructors to value their students employing metacognition in their courses.

Additionally, all types of metacognitive knowledge and skills were discussed by participants in each development group (no development, explicit, implicit, or metacognitive development with scaffolding), but each type of metacognitive skill was not discussed by instructors from each development group. Instructors who discussed expecting something metacognitive from their students in their exam question, came from every level of knowledge category. Thus for these instructors whether or not they discussed aspects of students' metacognition while discussing their exam question was not related to their knowledge of metacognition. Similarly, instructors who at some point in the interview mistook cognition for metacognition came from every level of knowledge category.

Conclusions and Implications

This study captured these instructors' pPCK about their students' metacognition, which is interwoven with their ePCK. As instructors discussed their teaching practices we were given a glimpse of their ePCK, and their thoughts from the reflection portion of the "Plan-Teach-Reflect" cycle. As discussed in the RCM, ePCK determines student learning outcomes (Hume et al., 2019). If an instructor does not have students' metacognition development as a part of their ePCK, it will be more difficult for instructors to implement it. Our study's results support this idea. We found that the eight instructors who had some knowledge of metacognition (could fully or partially define metacognition) all discussed ways they implement some type of metacognitive development for their students, thus possessing pPCK of metacognition allowed them to discuss how they implemented metacognition development in their courses. Even though 9 of the 17 instructors we interviewed either did not know of metacognition or could not define or describe it when asked, every instructor discussed learning strategies and habits that included some type of metacognitive knowledge and metacognitive skills in their interview. Thus, metacognition was not a foreign concept for any of these instructors, but there were some of them who were unfamiliar with the educational psychology terms for metacognitive knowledge and metacognitive skills. We identified more concerning gaps in the pPCK and cPCK of these instructors, besides their knowledge of educational psychology terms. With 12 instructors "mistaking cognition for metacognition" at some point in their interview, we can conclude that these instructors' pPCK of metacognition had some imperfections and gaps of knowledge. Also, the instructors who believed metacognition was solely their students' responsibility were lacking PCK about how students develop their metacognition within their course. As Stanton et al. (2015) found in their study with undergraduate introductory biology students, not all students know how to use their metacognition without some training. The instructors who believed it was the responsibility of another class to teach their students about metacognition were assuming that the learning context of their course included an undisclosed prerequisite of metacognitive training for the students. Another gap in knowledge was identified by some of the instructors in this study and could possibly be a gap in collective PCK. There were a few instructors who discussed a lack of training on metacognition development as a barrier to them implementing it in their courses. They discussed how training in educational theory and best practices was rare for post-secondary chemistry instructors, and often difficult to find or make time for. This lack of training was not only a gap in these instructors' pPCK, but a gap in the collective PCK of post-secondary chemistry instructors, due to the lack of instructional training required by most chemistry departments.

Though there was evidence that instructors who had knowledge of metacognition were already implementing metacognitive development, knowledge of metacognition was not essential for an instructor to develop their students' metacognition. We observed that seven of the nine instructors who had little to no knowledge of metacognition described ways they were already incorporating metacognitive development into their courses. An interesting example of this was Hector. Hector did not know the term metacognition before the interview, and once the interviewer described metacognition to him, he did not believe it was important for his students. Despite this belief, he described ways that he implicitly developed his students' metacognition, and how he valued study habits and ways of thinking for his students that the researchers coded as metacognition during his interview. When the interviewer described metacognition to Hector, he said he believed that metacognition was a subconscious process that his students already did, and so he believed it was unnecessary to incorporate a formal process for metacognition development into his course. For Hector, and instructors like him who do not see the relevance of the formal definitions of metacognition to their courses, we suggest advertising activities that "covertly" develop students' metacognition, along with their conceptual understanding of a topic in chemistry. Many activities that develop students' metacognition without explicitly discussing metacognition already exist for chemistry courses. A few examples of these types of activities currently exist in the literature (Bowen et al., 2018; Casselman & Atwood, 2017; Fishovitz et al., 2020; Kadioglu-Akbulut & Uzuntiryaki-Kondakci, 2021; Sandi-Urena et al., 2012; Ye et al., 2020; Young et al., 2019). Schraw et al.'s (2006) discussion of the Self-Regulated Learning Theory explains the importance of considering metacognition development along with students' cognition and motivation. Students who are self-regulated have strong metacognition, cognition, and motivation to succeed in an area, so it is important that instructors are considering metacognition and cognition together, and unnecessary for them to separate out these two areas of learning that are incredibly intertwined.

While we do think “covert” metacognitive activities are a good way to have instructors who are less interested in metacognition incorporate it into their courses, we cannot deny the benefits of instructor awareness of metacognition that we observed in our study. Activities that explicitly discuss metacognition with students through direct training can have benefits (Blank, 2000; Cook et al., 2013; Graham et al., 2019; Mutambuki et al., 2020; Swamy & Bartman, 2019; Visser & Flynn, 2018). As the RCM discusses, instructors’ pPCK influences their classroom practices (ePCK) (Carlson & Daehler, 2019). We observed that all of the instructors with some knowledge of metacognition discussed ways they were already implementing metacognition development in their courses. Since our results aligned with the model of how pPCK can affect ePCK, we believe raising instructor awareness of metacognition and how to incorporate metacognition development in their courses will increase instructor implementation. Awareness is also necessary to address the many gaps in knowledge we identified in these instructors’ pPCK of metacognition.

According to the Teacher-Centered Systemic Reform model (Gess-Newsome, et al., 2003; Woodbury & Gess-Newsome, 2002) of teacher beliefs, teachers will not seek to change their teaching practices unless they are unhappy with the current status quo. Instructors in this study indicated that they lacked training, wanted more training on how to develop their students’ metacognition in their courses, and discussed current barriers such as time and institutional constraints. Removing perceived barriers to reform does not necessarily lead to instructors implementing reformed teaching practices. Instead teacher beliefs may play a more important role (Gess-Newsome et al., 2003). We identified that these instructors' beliefs may align with improving efforts to develop their students' metacognition. Since we identified instances of instructors discussing their students' metacognitive skills and knowledge in every interview, regardless of an instructor's knowledge level or view of the importance of metacognition, these instructors were already familiar with student habits and practices that are metacognitive, even if they were unfamiliar with the educational psychology terminology. Since many of them made statements indicating they thought practices that we coded as metacognitive were beneficial for students, it appears that professional development to aid instructors in developing their students' metacognition would not struggle to demonstrate to instructors the relevance and importance of metacognition, if it showed them how developing students' metacognition in their courses aligns with their current beliefs. This knowledge combined with our observation that all of the instructors who knew something about metacognition were already implementing some development in their classes leads us to believe that raising instructors' awareness of the importance of metacognition is a feasible task that could lead to an increase in metacognition development in chemistry courses. An approach that relies on dissemination of documented resources to instructors may have a lower impact than desired and result in discontinued use over time (Henderson et al., 2012). Instead, change efforts that target whole departments, instead of individual instructors, over long spans of time may result in more sustainable change (Reinholz et al., 2019).

Limitations

Being a qualitative study, these findings are not generalizable, since there were only 17 participants, all undergraduate chemistry instructors at institutions in Colorado. But, the goal of qualitative research is not to be generalizable—our goal with this study was instead to be transferable (Merriam & Tisdell, 2016). By providing a rich description of the data collected, with detailed information to support the interpretation and conclusions we drew from the data, the reader can make an informed decision about how this study translates to their teaching and research practices.

A limitation in our data collection was that we did not employ any methods to accurately measure these instructors' understanding of metacognition, and the questions included in the interview guide are not specific enough to determine whether or not the instructors who said they knew what metacognition was had "sufficient" knowledge of the definition and relevant educational theories. The RCM of PCK discusses the importance of understanding an instructor's personal PCK, because this directly affects their classroom practices (their ePCK) (Carlson & Daehler, 2019). Thus, it was less important for us to evaluate these participants' understanding of metacognition, and more important to get a rich understanding of how they valued metacognition development for their students. According to the RCM, observing these instructors' classroom practices would also have been a way to capture how they valued metacognition development by observing the results of their enacted PCK (Alonzo et al., 2019). Thus, a limitation of this study is that we did not capture classroom observations, which could have provided an even deeper understanding of how these instructors valued metacognition.

Conflicts of Interest

There are no conflicts to declare.

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CHAPTER V

"REFLECTING ON HOW TO NOT CAREFULLY REFLECT": ENCOURAGING BIOCHEMISTRY STUDENTS' METACOGNITION

This chapter was submitted to the *Journal of Chemical Education*.

Contributions of Authors and Co-authors

Manuscript in Chapter V

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Contributions: Designed study. Advised on data collection and analysis. Conducted inter-coder reliability study. Reviewed and provided feedback on drafts.

Abstract

Many studies in science education research have found metacognition to be beneficial for undergraduate STEM students. Students do not necessarily know how to employ their metacognition without some training or prompting, and undergraduate chemistry instructors do not always have the capacity to instruct their students on metacognition. Thus, it would be beneficial for instructors and students if metacognition development could be implicitly incorporated into typical classroom activities. In this study, 25 undergraduate students in an upper-division biochemistry course were interviewed via a think aloud protocol. In the interviews, they were asked to solve two open-ended buffer problems. Before answering the second buffer problem, the students were asked questions designed to implicitly target their metacognition. The interview transcripts were qualitatively analyzed through a codebook thematic analysis, with a deductive coding scheme, to understand how these students employed metacognitive knowledge and metacognitive skills while solving the buffer problems. The transcripts were also analyzed to understand how these implicit metacognitive questions may have changed students' metacognitive approaches to solving the problems. Overall, 20 of the 25 students demonstrated some type of metacognition in response to the implicit metacognitive prompt that they had not demonstrated in the initial prompt. We discuss how asking students to think how an "unreflective" student would answer a question can prompt students to metacognitively evaluate their thought processes.

Introduction

Metacognition is the ability to think about your own thinking. There have been multiple studies in chemistry education research (CER) that have demonstrated the relevance and importance of metacognition for chemistry students (e.g., Bell & Volckmann, 2011; Casselman & Atwood, 2017; González & Paoloni, 2015; Hawker et al., 2016; Kelly, 2014; Mathabathe & Potgieter, 2014; Pazicni & Bauer, 2014; Rickey & Stacy, 2000; Sandi-Urena et al., 2012; Teichert et al., 2017). In their study of over one thousand general chemistry students Pazicni and Bauer (2014) confirmed the presence of the Kruger-Dunning effect (Kruger & Dunning, 1999) (when less skilled students overestimate their abilities, and more skilled students underestimate their abilities) in chemistry classrooms. Others (Bell & Volckmann, 2011; Hawker et al., 2016; Mathabathe & Potgieter, 2014) obtained similar results when they studied chemistry students' ability to predict or postdict their exam scores. Casselman and Atwood (2017) found that students could improve their knowledge of their knowledge (or metacognitive knowledge) with targeted training within a semester-long chemistry course. In their model of introductory chemistry students' perceived autonomy support, González and Paoloni (2015) found that metacognition was positively related to motivation and perceived autonomy support, and that students' metacognitive abilities predicted their performance in the course. Rickey and Stacy's (2000) study supported the idea that metacognition leads to success for students, when they found that two undergraduate students who were more metacognitive were able to more successfully answer an unfamiliar chemistry problem than the less metacognitive graduate student against which they were compared. Kelly (2014) found that general chemistry students with low metacognitive skills struggled to evaluate their understanding of molecular representations of conductive substances, which indicates that strong metacognitive skills can aid students in evaluating their understanding. Teichert et al. (2017) found that students who were able to effectively employ metacognitive monitoring of their understanding experienced more successful learning transfer at the end of the semester, when compared to the students who were not able to accurately monitor their understanding. From this research, it is evident that metacognition is important for chemistry students, and that with training chemistry students can grow and develop this skill.

In Stanton et al.'s (2015) characterization of introductory biology students' study plans, they found that more than half of biology students wanted to improve their study habits, but did not know how, and needed guidance on how to improve. This task frequently falls to instructors. Unfortunately, in undergraduate chemistry education, instructors may not have the knowledge required to train their students on how to be metacognitive (Heidbrink & Weinrich, 2021). A possible solution to this problem is for instructors to employ activities or assignments that can implicitly encourage students to be more metacognitive, without requiring instructors to invest time in training themselves how to teach metacognition. Talanquer (2017) asked students completing a concept inventory to also identify an incorrect answer that an unreflective or misguided student might answer. This activity increased students' performance on the concept inventory. Talanquer indicated that this increased performance could be due to this activity potentially prompting students' metacognitive awareness. However, the goal of Talanquer's study was to understand how asking students about an unreflective or misguided student could improve their scores on the concept inventory, and so investigating how those questions affected students' metacognition was outside the scope of Talanquer's study. Thus, we were interested in understanding how students use their metacognition when exposed to this type of prompting. The goal of this study was to investigate how a set of questions that could be incorporated into already existing assignments and activities could implicitly target students' metacognition, and to characterize the metacognition students demonstrated while answering these questions.

Theoretical Framework

The theory that guided the design and analysis for this study was metacognition, as discussed by Zohar and Dori (2012) and others (Schraw & Dennison, 1994; Veenman, 2012). Metacognition is frequently described as "thinking about thinking" and can be organized into two categories: knowledge of cognition and regulation of cognition. Metacognition has domain-general components; thus it is believed that strengthening a student's metacognition in one discipline should improve their metacognition in other disciplines as well (Veenman, 2012). Knowledge of cognition is also known as metacognitive knowledge and can be further subdivided into three types: procedural knowledge, conditional knowledge, and declarative knowledge. Procedural knowledge is knowing how to implement a learning strategy, such as how to organize notes in an effective manner, or test-taking strategies. Conditional knowledge is knowing when it is appropriate to implement certain learning strategies. For example, while taking an exam, a student may realize they do not fully understand a question, which would be the condition for them to engage a strategy to help improve their understanding, such as drawing a diagram to represent the question, or pulling out the important information from the question and organizing it in a more understandable manner. Their conditional knowledge would signal them to engage their procedural knowledge, which would be the strategies for gaining better understanding of the question. The third type of metacognitive knowledge, declarative knowledge, is knowledge of what you know, and what you do not know. This type of knowledge can also aid students in studying for exams, by allowing them to target the areas they do not know very well, instead of wasting time reviewing material they already know. Besides metacognitive knowledge, the other main component of metacognition is regulation of cognition, which is also known as metacognitive skills. Metacognitive skills can be further subdivided into five skill types: planning, information management, monitoring, debugging, and evaluating. Planning is exactly what it sounds like: making a plan, allocating resources, and setting goals prior to beginning a learning task. Information management is less intuitive—it is more about processing information than managing it and includes any skills or strategies that students employ to process information effectively. Examples of information management could be when a student draws a free-body diagram to better understand a physics problem (Taasoobshirazi & Farley, 2013), or when they employ a strategy to organize information given in a question prompt, like taking a question describing a chemical change and writing a chemistry equation to represent that change. Monitoring occurs mid-task when judgements are made of progress in the task. These judgements could be of the work the student has accomplished during the tasks, whether they are progressing towards the goal of the task, or of the thought process the student is engaging in to understand and complete the task. If a student realizes they have made an error while monitoring their progress, they can engage debugging, the fourth type of metacognitive skills, to find a solution to that error. Debugging is any strategy used to find and resolve errors in understanding or work while learning. Debugging can also be employed while a student is evaluating, the fifth type of metacognitive skills.

Evaluating takes place at the end of a task, when a student reviews their work and thought processes to determine if they are correct, and if they have fully accomplished the task. If a student encounters an error while evaluating their work, they could employ debugging strategies to fix the error.

These definitions of metacognition, metacognitive knowledge, and metacognitive skills guided the analysis of the interview data. The research questions that informed how this theory of metacognition was applied to our data were:

Research Questions

Q1 How do undergraduate biochemistry students employ metacognitive skills and metacognitive knowledge when solving buffer problems?

Q2 In what ways does implicitly targeting metacognition change a biochemistry student's metacognitive approach to solving buffer problems?

Methods

Undergraduate students were recruited from a 300-level biochemistry course (designed for chemistry, biology, sports and exercise science, and dietetics majors) at a large, public university in the Rocky Mountain region of the United States. The students were recruited by an in-class announcement that briefly described the study and an email invitation to sign up for an interview time. Twenty-five students gave informed consent to participate in this study. In the interviews, students were asked to solve two buffer problems (see figure 5.1 for questions), which were taken from the Chemical Thinking curriculum (Talanquer & Pollard, 2010, 2017) and used with Talanquer's permission. We chose buffer solutions to be the conceptual focus of the activity because buffers are a difficult topic for chemistry students at all levels of training, and they are a relevant concept for multiple areas of chemistry (Orgill & Sutherland, 2008). Since the two buffer questions required students to display different knowledge and understanding of buffers, we varied the order of the questions—twelve of the students answered the questions in the order in figure 1, while thirteen answered them in the reverse order. For the first problem, students were simply asked to solve the problem while voicing their thoughts, and the interviewer asked probing questions (such as: "What do you notice about the problem?" and "Can you tell me more about ___?") to try and elucidate their thought process. Before beginning the second problem, the students were asked a series of questions which were meant to implicitly prompt their metacognition. Two of these questions were developed based on Talanquer's (2017) study, where he asked students to answer a concept inventory in the way that a student who "does not carefully reflect on what the question is asking or are misguided by their intuition" (Talanquer, 2017, p. 1807) might answer. All the implicit metacognitive prompting questions asked students to think about another student and how they might answer the question. After students answered these implicit metacognitive prompts, they were asked to solve the second buffer problem while voicing their thoughts aloud again. (See figure 2 for the implicit metacognitive prompting questions, and for full interview protocol, see Appendix M).

Figure 1

Buffer Problems

Buffer Design: "*Buffers can be prepared by directly combining the acid/base conjugate pair or by inducing reactions that generate them in solution. Imagine that you wanted to prepare a buffer containing equal concentrations of HNO_2 and NO_2^-. These are the substances you have available to complete your task: H_2O, HNO_2, KNO_2, HCl, NaOH. Propose three different strategies to prepare the targeted buffer. Justify your reasoning.*"

Buffer pH: "*Imagine that you use 0.6 moles of HCN (pKa = 9.2) and 0.5 moles of NaCN to prepare two different buffer solutions. In one case you add these amounts to a beaker with 100 mL of H_2O. In the other case, you add the same amounts to another beaker with 200 mL of H_2O. Which of the two buffer solutions will have a lower pH? Clearly justify your reasoning.*" (Talanquer & Pollard, 2015, p. 394)

Figure 2

Implicit Metacognitive Prompts

1) What is a way of thinking about this problem that might lead a student astray?
   Follow-up: Why do you think a student would do that?
2) Can you describe how a student who "does not carefully reflect on what the question is asking" might work through the problem? (Talanquer, 2017, p.1807)
3) Can you describe how a student who is "misguided by their intuition" might think about and answer this problem? (Talanquer, 2017, p.1807)
4) Is there something specific about buffer problems that would cause someone to mess up their solution to this question?
   Follow-up: Why is [__] confusing?
5) What would that student miss in this problem? What would they get right?
   Follow-up: Why do you think that?

Each interview was recorded and later transcribed verbatim. Livescribe drawings (Linenberger & Bretz, 2012) of the students' work were collected as artifacts, and at the end of the interview the first author also collected demographic information and students' responses to the Revised two-factor Study Process Questionnaire (R-SPQ-2F) (Biggs et al., 2001) to measure students' approaches to learning. The survey data was collected to see if a "deep" or "surface" approach to learning was relevant to characterizing the metacognition demonstrated by students in this study.

Zohar and Dori's (2012) framework of metacognition composed the deductive codebook, which was applied to the data according to Braun et al.'s (2019) "codebook thematic analysis" process (See Appendix P for codebook). All interview transcripts and Livescribe drawings were analyzed for metacognition. Metacognition was measured in two different ways during analysis: "presence" and "frequency". The first method, "presence", reported if a specific type of metacognition was present or not during the interview. For the "presence" count, if a type of metacognition was used at least once in an interview it was recorded as "present". We conducted a "presence" analysis for students' entire interviews, and also broke it down by if the code was present in the first or second buffer problem. Thus, we had three measures of "presence": "entire interview presence", "Q1 presence", and "Q2 presence". The second method measured the frequency of the different types of metacognition present in these interviews. For frequency, we counted the number of codable units that had each type of metacognition. The "codable unit" (O'Connor & Joffe, 2020) was determined by chunking different sections of text that represented a complete thought or idea discussed by students in their interviews. Each code was applied a maximum of one time to a codable unit. The number of codable units varied from interview to interview, depending on how talkative each individual student was. "Frequency" counts of each type of metacognition were measured for each interview in its entirety. We only report "entire interview frequency" counts because most students spoke more during the second question. Since the Q2 sections were longer on average, it was possible that the "frequency" counts could be inflated in Q2. Thus, we only relied on the "Q1 presence" and "Q2 presence" counts when comparing the metacognition demonstrated by students in the two questions.

The researchers assigned scores to students' written and verbal responses so that we could compare students' performance on the problems with the metacognition demonstrated in their interviews. To create the scoring rubric, we grouped responses of similar quality together as if grading on an exam and found that for both questions four categories emerged, which were assigned scores from 0-3 (a detailed description of these categories can be found in Appendix O). Thus, the students' written and verbal responses to each of the two buffer questions were scored on a 0-3 scale, and then summed to calculate their overall score, which was from 0-6. The R-SPQ-2F survey responses were analyzed according to Biggs et al. (2001) to measure students' approaches to learning in their biochemistry course.

Many steps were taken to maximize validity and reliability of this study. The first author kept detailed memos of all her thought processes for assigning codes, to ensure coding was consistent. Memos were also kept for all decisions made for the analysis process. The first and second author met weekly to discuss the project, and the second author conducted an intercoder reliability study (O'Connor & Joffe, 2020) on 20% of the data set (5 interviews). There was originally 96% agreement, but all coding disagreements were discussed until agreement was reached. This research was approved by the Institutional Review Board of the University of Northern Colorado.

Results

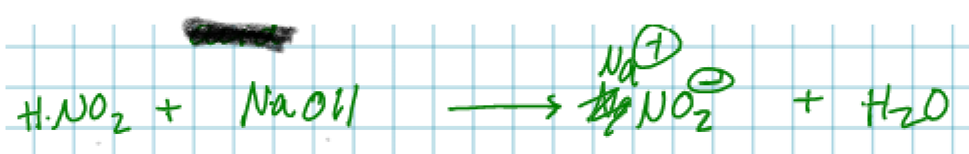
Research Question 1

To answer our first research question: "How do undergraduate biochemistry students employ metacognitive skills and metacognitive knowledge when solving buffer problems?" we examined the "entire interview presence" counts for each type of metacognition. All twenty-five of the students demonstrated both metacognitive knowledge and metacognitive skills in their interviews. All eight types of metacognition were present in the data set, but not every interview demonstrated all eight. The most common type of metacognitive knowledge was declarative knowledge, which was present in all twenty-five interviews. Declarative knowledge was most frequently expressed in these interviews as statements that indicated the students had an awareness of their limitations and abilities with solving buffer problems. Procedural and conditional knowledge were much less common and only present in twelve and six interviews, respectively. In the following quote, Participant 20 demonstrates all three types of metacognitive knowledge:

> I'm good at math… I can figure out from [an] equation, okay you plug in here to here and then this and this and then solve it. I can do that. But when I don't have an equation and I'm just given values and it's like just know it, that's when I run into problems because I can't memorize 4 million equations. My head, it doesn't like doing that. And so for me it's just easiest to then break it apart and better understand it. Try and visualize it for myself if I can't like physically do it. (Participant 20)

Participant 20 discusses her awareness of her strong math abilities, but also an awareness that she is not capable of memorizing every math equation—both statements discuss her knowledge of her knowledge, thus declarative knowledge. She also knows that when equations are not provided she should enact the learning strategy of breaking apart the question and trying to visualize what is happening, so that she can answer the question. In that statement, she demonstrates conditional knowledge and procedural knowledge, with the condition being "when I don't have an equation" and the learning procedure or strategy being to "break it apart and…try to visualize it for myself".

The most common type of metacognitive skills demonstrated in the interviews was information management. This is unsurprising because the definition of information management is any "Skills and strategy sequences used on-line to process information more efficiently" (p. 474-475, Schraw & Dennison, 1994), and we interpreted writing as a strategy for efficiently processing the information in the problems. We prompted students to write by providing the Livescribe notebook (and in the interviews, the first author did encourage many students to write out their thoughts, to make it easier to ask them questions). Since they were prompted, we disregarded information management codes related to what the students wrote. The second most common type of metacognitive skills was monitoring, which was present in twenty-three of the interviews, and was usually demonstrated as students' appraisal of their thought process or work in solving the problem. Below is an example of Participant 17 monitoring her understanding while answering the Buffer pH problem:



> So that seems right […] Um, so I think that that could work […], I dunno if that's considered a buffer system 'cause I think they're supposed to be something in the middle…I think that's what I would probably end up putting for one of those strategies. (Participant 17)

While working through the Buffer design problem, Participant 17 wrote out a possible equation for a buffer system. In this quote, she made an appraisal of her work, and decided it could be a solution, though she was not certain. For the rest of the metacognitive skills, evaluating and planning were both demonstrated in nineteen of the interviews, while debugging was the least common form of metacognitive skills and was only present in three of the interviews. It is possible debugging was so scarce because it not only required students to make an error in their work or thinking about the problem, and then become aware of that error, but also to choose to try and correct the identified error. Many of the students were unaware of errors they made, and even some who realized they had made mistakes chose not to correct them.

The results from the R-SPQ-2F survey did not differentiate the students from each other very much, except for two students, participant 23 and participant 7. The possible scores for the R-SPQ-2F survey were from 10-50, on two different scales, the "deep approach" (DA) scale and the "surface approach" (SA) scale. These students' range of scores for the DA scale was 17-40, with the average score being 26.4. For the SA scale scores ranged from 16-41, with an average score of 25.3. Participant 23 scored very high on the DA scale, and low on the SA scale (DA = 40, SA = 23), which indicates that this student employed deep approaches to learning in this biochemistry course. Participant 7 had a low score for the DA scale, but a high score on the SA scale (DA = 17, SA = 41), which indicates this student employed a surface approach to learning in this biochemistry course. Neither participant demonstrated much metacognitive knowledge, but they differed in the metacognitive skills they demonstrated. Participant 23, the "deep learner", demonstrated "evaluating" and "monitoring", while participant 7, the "surface learner", did not demonstrate these skills in her interview. In the following quote, participant 23 reflects on the answer he gets for the Buffer pH problem and decides that it makes sense:

> So I got the same answer for both solutions. [pause] And that, I mean, to me that makes sense because if you put it in water, both of these solutions are gonna dissociate, um, fully. So it would make sense that it would kind of have a one-to-one ratio between what you put in and what's dissociating in solution. So yeah, it makes sense that it would be the same pH for both of them and the volume of the water wouldn't change what, um, I guess the pH of the solution. (Participant 23)

After arriving at an answer, and before moving on to the next question, participant 23 takes a moment to evaluate whether his answer is feasible. After taking into account his knowledge about buffer systems, he decides that his answer is reasonable.

Further, in characterizing students' metacognition, we compared how well students performed on the two buffer questions (their scores) to their metacognition. We first investigated whether the implicit metacognitive prompts affected students' performance on the buffer problems. We found that overall students scored lower on the buffer design question than the buffer pH question, but the order of the questions (and therefore whether students experienced the implicit metacognitive prompts prior to solving the questions) did not appear to affect students' scores on the buffer problems. Thus, when we investigated the relationship between students' metacognition and their performance on the buffer questions, we took into account the metacognition demonstrated in the entire interview. In order to investigate a possible relationship between students' metacognition and their scores on the buffer problems, we analyzed the "entire interview frequency" counts of the different types of metacognitive knowledge and metacognitive skills and compared this to how they scored on the buffer problems. In this analysis, we found that that students who scored higher (5, 6) on the buffer problems and students who scored lower (0, 1) on the buffer problems demonstrated a similar amount of metacognitive knowledge and skills. Surprisingly, the students who scored the highest and lowest appeared to demonstrate less metacognition in their interviews. Students who scored in the middle (2, 3, 4) were the ones who demonstrated the most metacognition in their interviews. The students who seemed to be in the middle of gaining knowledge about buffers—some knowledge existed in their schema, but the questions were still a bit of a struggle to answer—were the ones who demonstrated the most metacognition in their interviews.

Research Question 2

To answer our second research question, "In what ways does implicitly targeting metacognition change a biochemistry student's metacognitive approach to solving buffer problems?" we compared the metacognition coded in the first buffer problem of the interview to the second. During analysis the questions were graded, and then compared to see if the order of the questions influenced students' ability to answer them. In general, the Buffer pH problem was easier for students than the Buffer Design problem, regardless of question order. The number of students in each scoring group was similar regardless of question order and so we can conclude that our characterization of student changes from Q1 to Q2 were due to changes in students' metacognition. A summary of the changes in presence of the different types of metacognition (excluding information management and debugging, since information management was prompted and debugging was only present in three interviews total) can be seen in Table 5.1. Table 5.1 reports the "presence" counts of these types of metacognition in

Q1 and Q2, thus how many interviews had each type of metacognition present for Q1 compared to Q2.

Table 5.1

Changes in Presence of Metacognition from Q1 to Q2

Type of Metacognition	Q1	Q2
Metacognitive Knowledge	22	25
Declarative Knowledge	21	25
Conditional Knowledge	1	5
Procedural Knowledge	9	9
Metacognitive Skills	22	24
Planning	16	12
Monitoring	20	23
Evaluating	7	16

Changes in Metacognitive Knowledge

Metacognitive knowledge was present in only 22 interviews for Q1, while all 25 demonstrated it in Q2. We also observed this increase from Q1 to Q2 for conditional knowledge and declarative knowledge. Procedural knowledge occurred in equal numbers of interviews for Q1 and Q2. When we examined subnodes of declarative knowledge more closely, we observed that examples of students expressing that they “know what they do not know” almost doubled from Q1 to Q2 (present in eight interviews for Q1 and 15 for Q2). The only type of declarative knowledge that decreased from Q1 to Q2 was examples of students discussing that they “do not know what they know”.

Changes in Metacognitive Skills

Metacognitive skills were present in every interview, but there was a higher presence of evaluating in Q2 than in Q1. Statements where students demonstrated their evaluating skill that increased from Q1 to Q2 were: while reflecting after finishing the problem, the student identified areas where they struggled while solving the problem, and while reflecting, the student made statements that indicated they thought their work and answer was sufficient. Monitoring also increased slightly in presence from Q1 to Q2, though regardless of question order, we saw more interviews with monitoring during the Buffer design question. We believe this was because it was a less familiar question type for the students, though we were encouraged to observe that these students employed monitoring for the less familiar question. "Appraisal of thought process" and "appraisal of work" both increased from Q1 to Q2 (“appraisal of thought process” was present in 12 interviews for Q1 and 17 interviews for Q2, while “appraisal of work” was present in 10 interviews for Q1 and 13 for Q2) , though the change was more dramatic for "appraisal of thought process" when they answered the Buffer pH question for Q1 and then the Buffer design question for Q2 (increased from 5 to 11 interviews in this case). Students monitoring by checking their reading comprehension increased from Q1 to Q2 (9 for Q1 and 13 for Q2).

Planning was the only type of metacognitive skills which decreased in presence from Q1 to Q2. This could have been caused by the implicit metacognitive prompting giving students an opportunity to accomplish more planning subconsciously, while they were thinking about the "other" student. There was an interesting trend in how students planned by allocating resources--regardless of order, more students did this before beginning the Buffer pH problem—only 2 students demonstrated planning before the Buffer design question, while 10 demonstrated it before solving the Buffer pH question. We believe this was due to the Buffer pH problem being more familiar to these students and so they had an existing algorithm for how to set it up. The "goal setting" aspect of planning decreased from Q1 to Q2 (present in nine interviews for Q1 and 5 interviews for Q2). We believe this was again due to the implicit metacognitive prompting questions allowing students to think more about the problem before beginning to solve it themselves. Evidence of students "making a plan" was present more often when students were answering the Buffer design question, regardless of if it was Q1 or Q2 (present in 13 interviews while answering Buffer design and 5 interviews while answering Buffer pH).

Metacognitive Changes for Individual Students

While conducting the analysis of the changes in metacognition reported in Table 5.1, we were curious about possible relationships between those changes (e.g., are the four students who increase in declarative knowledge the same who increase in conditional knowledge?) and decided to investigate how each student's metacognition changed during the interview. We found that of the 25 students who participated in this study, 20 students demonstrated some type of metacognition in Q2 (the implicit metacognitive prompting section) that they had not demonstrated in Q1. Of these 20, five students both increased and decreased in different types of metacognition from Q1 to Q2.

Upon further investigation of the five who did not increase in metacognition from Q1 to Q2, we found that one of them did not demonstrate any changes in metacognition—she consistently employed declarative knowledge, planning, monitoring, and evaluating throughout the interview. The remaining four students demonstrated some metacognition in Q1 that they did not in Q2 and did not demonstrate any new metacognition in Q2— they decreased in types of metacognition demonstrated. The decreases for these four students and the fluctuations we saw for five of the students who increased in metacognition indicate that this activity did not make all students become more metacognitive. Despite this, the findings that 20 students increased in their metacognition during a brief interview indicates that these questions may be prompting their metacognition.

Figures 3, 4, and 5, are three different Sankey diagrams which represent the changes to individual students' metacognition from Q1 to Q2. The lines, or "flows" represent individual students, and the flow thickness represents how many students were in that particular flow. Thus, the thicker the flow, the more students being represented. Horizontal flows represent no change. For example, in Figure 4, the horizontal green flow at the top of the figure represents the students who demonstrated procedural knowledge during both buffer questions, and the horizontal green flow at the bottom of the figure represents the students who did not demonstrate procedural knowledge at all during their interview. The diagonal flows represent a change that took place. The flows that have a negative slope represent types of metacognition that students demonstrated in the first question, but not the second. Flows with a positive slope represent types of metacognition that students demonstrated in the second question but not the first. Returning to procedural knowledge in Figure 4, from this diagram we can see that even though the Q1 presence counts and Q2 presence counts for procedural knowledge were the same (as reported in Table 5.1), they were not the same students. The green diagonal flows represent the students who only demonstrated procedural knowledge during one of the questions.

Figure 3

Changes in Individual Students' Metacognitive Knowledge and Metacognitive Skills

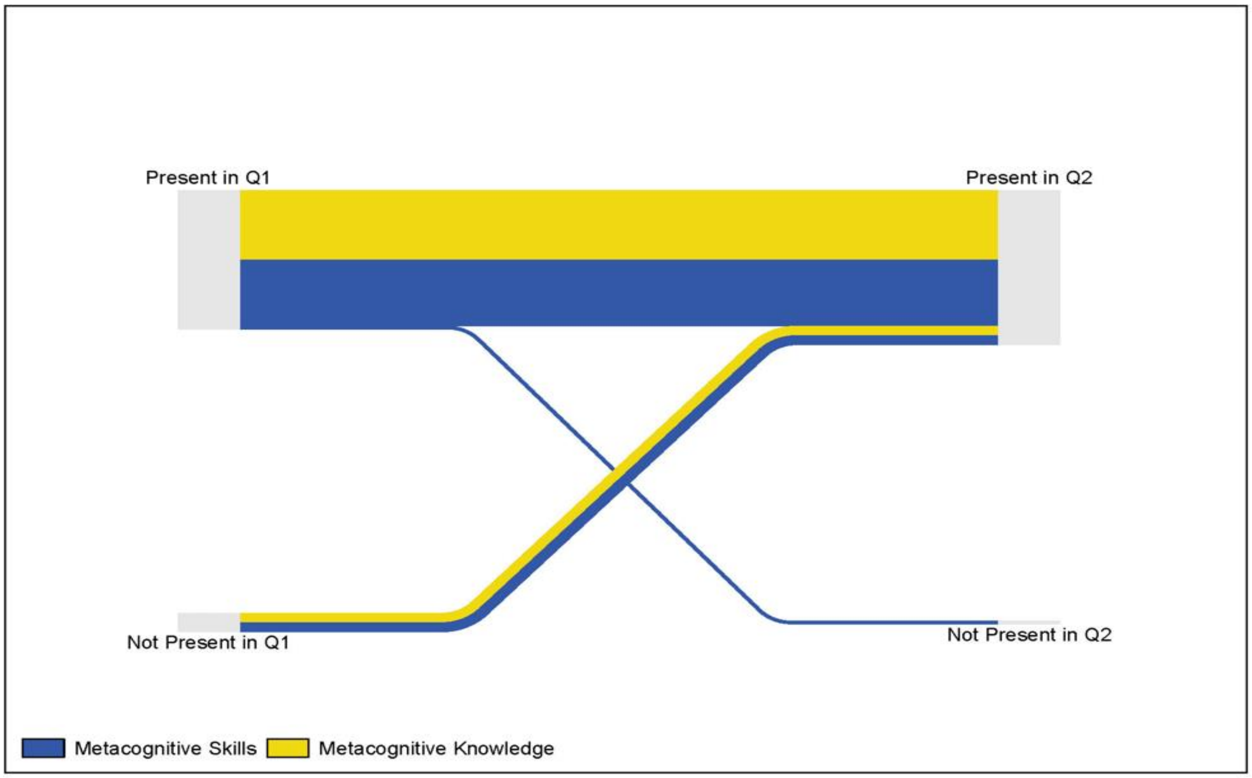


Figure 4

Changes in Metacognitive Knowledge types for Individual Students

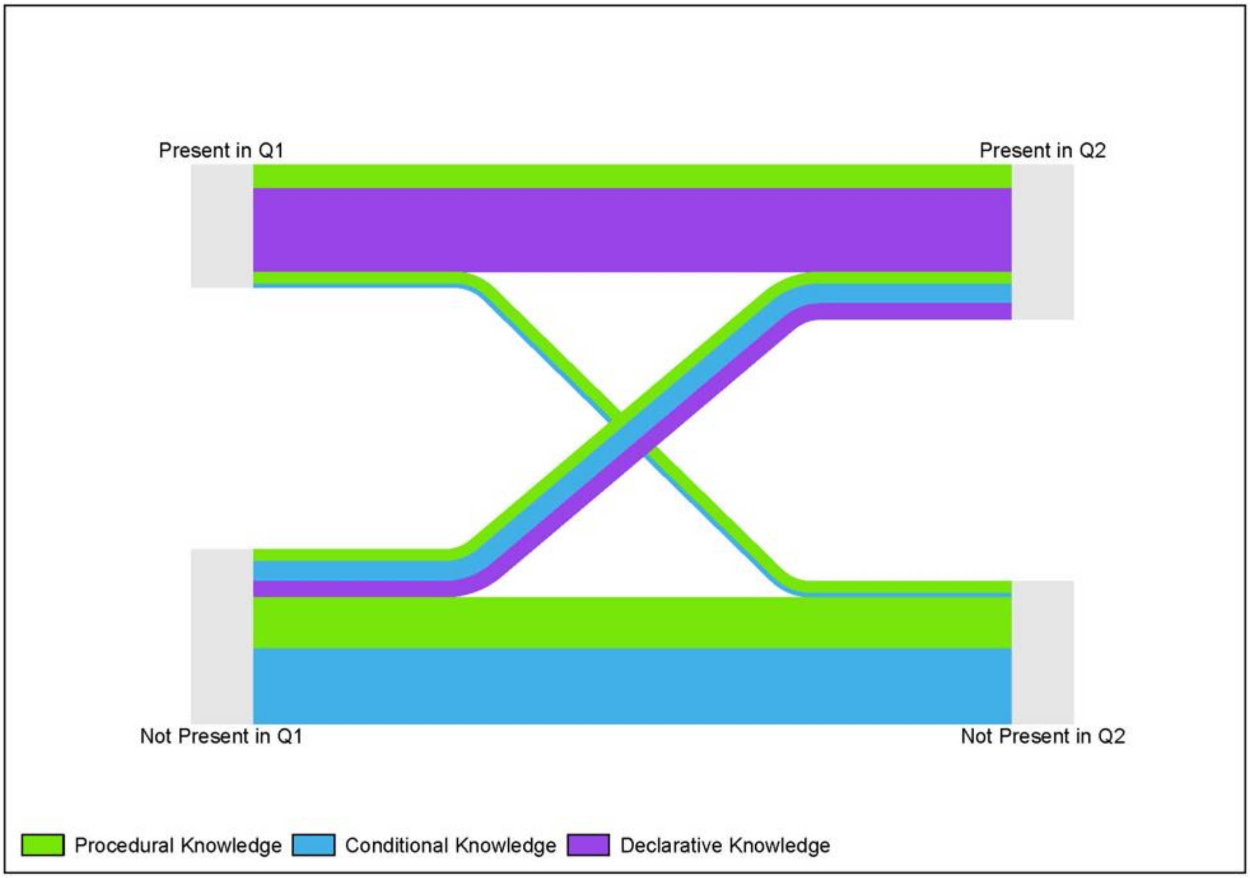
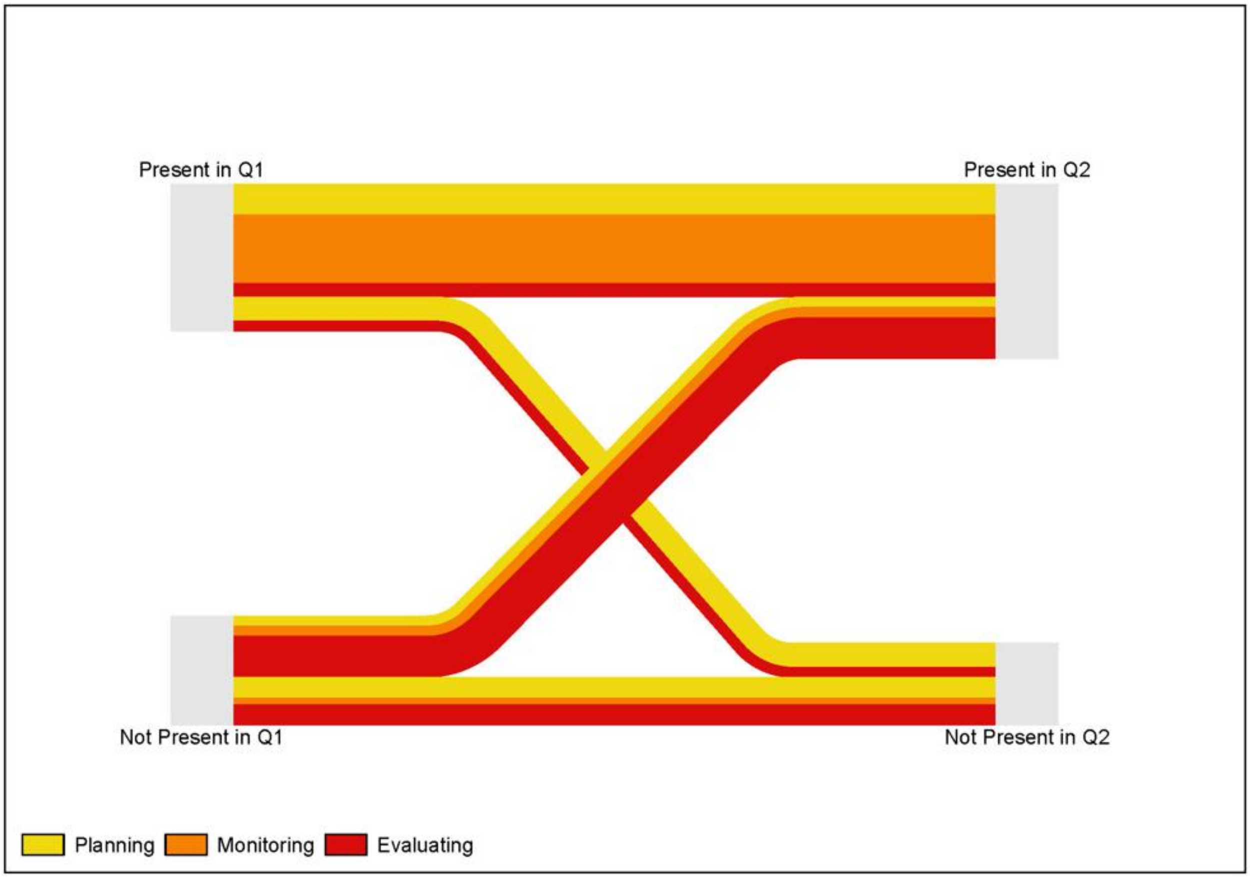


Figure 5

Changes in Metacognitive Skills types for Individual Students



The metacognition most commonly displayed only after implicit prompting (Q2 but not for Q1) was evaluating. Twelve students did not employ evaluating while answering the first question but did use it during the second question. For the four students who did not demonstrate a new type of metacognition after the implicit metacognitive prompts, they usually did not demonstrate the metacognitive skill of planning during Q2. Again, the students may have been planning more subconsciously while they were thinking about the "other" student. From this analysis, it appears that these implicit prompts were most effective in prompting students to evaluate their work and thought processes. However, there were students who demonstrated increases in all types of metacognitive knowledge, and the metacognitive skills monitoring and planning during Q2.

Voice

We were surprised to observe that all twenty-five students responded to at least one of the implicit metacognitive prompting questions, which were phrased about a different student, in the first person. This can be seen below in a quote from Participant 1:

> R: Could you describe how a student who doesn't carefully reflect on what the question is asking might work through the problem?
>
> P: I guess, like, if I just read this but felt kind of hurried to, like, oh I just need to put something down, I would only, I feel like, knowing how I think in exams, I would only look at what I'm given to complete, but then forget what I am actually looking for. (Participant 1)

Like Participant 1, many students answered the metacognitive questions purely from their own perspective, which was evidence that these questions encouraged students to think about their own thinking. In some instances, students responded by speaking about multiple perspectives—using “I”, “you” and “they” to express how the “other” student would approach the problem. Below is an example of a student who moved between speaking in first person and second person while answering an implicit metacognitive prompt:

> R: Could you describe how a student who isn't carefully reflecting on what the question is asking, how they might work through the problem?
>
> P: Okay, um at least for me like you gotta--like sometimes in the actual question it'll give you a whole bunch of these amounts, […] I feel like you come across a question like this and you're like, "Well ok, I have to use all these numbers in order to get the actual answer," and then later on your professor goes back and says 'oh yeah that number I just put up there in the question--you didn't have to use it at all. But that's how you knew the equation or not.' (Participant 24)

Responses like the one above were fairly common. We did not code responses like these as metacognition because the student does not use "I" consistently throughout their response, and so these ideas may not be the result of them thinking about their thinking. We referred to quotes like these as demonstrating "transitional metacognition". Students expressing "transitional metacognition" may still be in the process of developing the ability to think about their thinking, and so when we asked them these implicit metacognitive questions, their responses came out in a mixture of perspectives. They seemed torn between answering fully in third person about the "other" student and answering in first person about their own thoughts. In all 25 of the interviews, students responded either fully in the first person, or from a mixed perspective like the response above.

Discussion

The goal of this study was to investigate how students employ metacognitive knowledge and skills while solving buffer problems, and to investigate if implicit metacognitive questions could encourage students to be more metacognitive. We were pleased to observe that these biochemistry students employed all eight types of metacognition, with declarative knowledge being the most common type of metacognitive knowledge, and information management (in the form of writing to process information more efficiently) the most common type of metacognitive skills, with the second most common type being monitoring.

When we compared the first phase of the interview to the second phase (Q1 to Q2), we found that there were differences in how students employed their metacognition. The implicit metacognitive questions—which were asked before students began the second problem—encouraged students to spend more time actively engaged with the material in the buffer problems. Because of this, students talked more on average during the second part of the interview, and we observed an increase in the presence of many of the metacognition codes from Q1 to Q2. If these implicit metacognitive prompts were to be incorporated in a classroom activity, one of the benefits could be for students to actively engage in their thinking about a problem. In particular, this activity may prompt them to spend more time actively thinking about their thought processes. In his 2017 study, Talanquer found that students who completed a concept inventory, and were also asked to consider what a “misguided” and “unreflective” student would select, scored higher than the students who simply answered the inventory. He concluded that the increased scores were due to the instructions “Select the option below that you think is most commonly chosen by students who get this question wrong because they do not carefully reflect on what the question is asking or are misguided by their intuition” (p. 1807, Talanquer, 2017) potentially implicitly prompting students’ metacognition. Our results characterized the types of metacognition employed by students when interacting with these types of prompts. We found that asking students questions about how a different student might answer the given question and go astray in their solution, or how a misguided or unreflective student may answer the question, implicitly prompted students to be more metacognitive. This difference was most evident in students' use of evaluating.

When comparing students' performance on the problems and the metacognition they demonstrated, we found that the students who scored in the middle range on the buffer scores demonstrated more metacognition. We believe this is related to where a student's understanding of buffers was in Vygotsky's Zone of Proximal Development (Vygotsky, 1978) when they participated in the study. Our theory is that students who demonstrated more metacognition are still developing their understanding of buffers. As Vygotsky describes, their understandings of buffers "have not yet matured but are in the process of maturation, [understandings] that will mature tomorrow but are currently embryonic in state" (Vygotsky, 1978, p. 86). Because these students were still developing their understanding, they were able to engage with the questions but needed to employ their metacognition to regulate their processing of the problem. Students who scored very low or very high did not demonstrate as much metacognition, because they either did not possess enough knowledge to engage much with the material, (the questions were too difficult to be in their zone, they did not yet have even an "embryo" of understanding) or it was too easy for them to require thinking about their thinking to occur (their understanding of buffers was fully matured). Investigating this relationship between metacognition and the zone of proximal development was outside the scope of this study but could be an area for future research. This could also be something to keep in mind for implementing these questions in a classroom setting—if students do not have a sufficient existing schema to understand the material, they will struggle to engage their metacognition, and if the question is too easy, they also may not consciously employ their metacognition.

Conclusions and Implications

In this work, we have found that asking students to think about another student's way of thinking implicitly prompts students' metacognitive evaluating. The questions we used to do this can be easily incorporated into existing assignments and activities, and they could be an option for undergraduate chemistry instructors to incorporate metacognition development into their courses without a large time investment in developing skills and knowledge to teach metacognition to their students.

Limitations and Future Work

In this study we interviewed these twenty-five students one time to characterize their metacognition, and any differences they may have demonstrated after implicit metacognitive prompting. From this one interview we did observe changes, but we know that a twenty-minute interview is unlikely to cause sustainable change for these students. A limitation of this study was the short window of time in which we collected data, but we believe our results warrant future investigation into how implicit metacognitive prompts may develop students' metacognitive abilities. Future work could explore how engaging with these questions in multiple activities and assignments across a semester could develop students' metacognition.

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CHAPTER VI

CONCLUSIONS AND IMPLICATIONS

Approaches to Teaching Inventory Data Results and Discussion

The survey data from the Approaches to Teaching Inventory (ATI) (Trigwell & Prosser, 2004; Trigwell et al., 2005) was not included in the manuscript reporting the findings of the instructor study because only ten participants responded, out of the sixteen I was able to send it to. (One instructor moved in the year between the interview and the survey recruitment, and I was unable to locate him at his new position.) Also, I was concerned about validity issues with administering the survey a whole year after conducting the interviews, because the instructors' beliefs about teaching could have changed in that time. But I do not want to conclude this dissertation without answering the fourth research question from the instructor study, which was: How are these postsecondary chemistry instructors' views on metacognition related to their approaches to teaching, as measured by the Approaches to Teaching Inventory?

The ATI scores instructors on two scales: The Conceptual Change Student-Focused (CCSF) scale and the Information Transfer Teacher-Focused (ITTF) scale, both which have a possible score range of 8-40. For the ten instructors who responded, the CCSF scores had a range of 18-39, and an average score of 31. For the ITTF scale the range was 20-33, with an average of 26. When the averages of these two scales are compared it appears that these instructors lean towards or believe that they employ student-centered teaching practices, but the average score of 26 on the ITTF scale indicates that they still implement at least some teacher-centered teaching practices.

Due to the nature of the two scales, it should be unlikely for a respondent to score high scores on both scales, and if high scores are recorded for both the CCSF and ITTF for an instructor, it can indicate a validity error has occurred. Upon closer analysis I found that three of the ten instructors who responded had scored a 30 or higher on both scales. There are a few reasons for why these instructors may have earned these scores. They may have mis-interpreted the ATI prompts as “what a good teacher does”, and probably believe themselves to be good teachers, so they responded to each question with a 4 or 5 out of 5. They may have simply not read the prompts thoroughly and just selected 4 or 5 for all of their responses, or they may be familiar with research discussing the benefits of student-centered active learning and have a desire to implement those practices, but actually still employ teacher-centered practices, which would earn them high scores on both scales. Without observational data of their teaching practices there is no way to confirm what caused these three instructors to score highly on both scales, and so I will not discuss their scores in relation to their views of metacognition.

Of the seven remaining instructors who responded to the survey, two scored higher on the ITTF scale than the CCSF scale, four scored higher on the CCSF scale, and one earned the exact same mid-range score on both scales. I sorted these seven instructors by either their high CCSF score, high ITTF score, or their equal score on the scales, and then analyzed how their interviews were coded for how these instructors valued metacognition, what practices they were already implementing to develop their students’ metacognition, their level of knowledge of metacognition, and their suggestions for improving metacognition development in undergraduate chemistry education. Overall, there were no large differences between the three groups of instructors in any of these four areas. I will discuss the changes that I did observe, though I cannot make any conclusive statements about these trends due to the nature of this data collection.

When I investigated any differences in how these seven instructors valued metacognition, there were very few differences. All seven believed metacognition was important for students in their course, there were no differences in how the three groups valued metacognitive knowledge and skills (CCSF and ITTF high scorers had a mix of those who valued metacognitive knowledge and metacognitive skills and those who did not), none of these instructors saw metacognition development as purely the student's responsibility, and there were not any differences in why they believed metacognition is important (the reasons were evenly mixed among participants). The only small difference I observed was that all of the CCSF high scorers believed that metacognition was the instructor's responsibility, and should be taught in every class, but one of the ITTF high scorers also held this belief. The remaining two valid responses were for the other high ITTF score and the equal scorer, and they both believed that metacognition should be taught in another class.

How these instructors developed their students' metacognition also had very few differences. All of these instructors implemented some type of development, though the two instructors who scored highly on the ITTF scale only employed implicit metacognition development. There was also one instructor who scored highly on CCSF who only used implicit metacognition development. The other three high CCSF scorers and the equal scorer all used either implicit metacognition development with scaffolding alone or combined with implicit metacognition development without scaffolding. The equal scorer was the only one who did not know of metacognition prior to my interview. Only six of the seven instructors were asked about their suggestions for metacognition development, and there were no major differences in suggestions from the six who responded.

I also investigated any possible differences between the group of ten instructors who responded to the ATI, and the six who were invited to respond but did not. I examined the same four groups of codes: how these instructors value metacognition, how they implement metacognition development for their students, what their level of knowledge of metacognition was, and their suggestions for improving metacognition development in chemistry education. While comparing and contrasting the instructors who responded to the ATI against those who did not respond, I did not observe any trends. Like my analysis of the valid ATI responses, the differences I observed were small, and I am unable to make any claims or draw any conclusions from these observations, but I will still report what I found below.

In regards to how these instructors valued metacognition, there were no large differences in the respondents and non-respondents for what level of importance they assigned metacognition development. There was also no observable trends for whether or not they valued metacognitive skills and metacognitive knowledge. There were some differences observed relating to the instructors' beliefs about who was responsible for teaching students about metacognition. Seven out of the ten respondents believed that every instructor should teach metacognition, while only two of the six who did not respond believed the same None of the respondents believed that metacognition was solely the students' responsibility, but three of the six non-respondents held this belief. There was also a possible difference in why the respondents and non-respondents thought metacognition was important for their students; five of the ten respondents believed that metacognition leads to success, while only one of the six non-respondents had made statements indicating this during their interview.

There was only one notable difference in how the respondents and non-respondents developed their students' metacognition: all of the respondents employed some type of metacognition development already, while the two participants who did not implement any type of metacognition development were also part of the non-respondent group. The remaining four instructors in the non-respondent group did implement some type of implicit metacognition development—either with or without scaffolding, and so they were not different from the ten instructors who did respond to the survey. There were no differences observed between the respondent and non-respondent groups for their level of knowledge of metacognition, or their suggestions for metacognition development.

From this analysis, I cannot make any conclusions about how an instructor's approach to teaching was related to their perspectives of their students' metacognition development. A possible future study could answer this question by combining the ATI with a survey aimed to measure instructors' beliefs about metacognition.

Conclusions and Implications

The goal of the research reported in this dissertation was to investigate metacognition development in postsecondary chemistry education. In my instructor study, I learned about how seventeen postsecondary chemistry instructors in Colorado valued metacognition, what practices they were already implementing to develop their students' metacognition, and their suggestions for improving metacognition development in chemistry education. The majority of these instructors valued metacognition, and believed it was important for students in their courses. These instructors regarded metacognition with varying levels of importance, but all except two of them believed metacognition could be beneficial for their students. Many of these instructors were able to describe ways they were already encouraging their students to be more metacognitive, either by explicitly discussing the importance of metacognition in their class, discussing the importance of study habits and practices that were metacognitive in nature, or by implementing activities that implicitly prompted students' metacognition. Only two of the seventeen instructors did not discuss any ways that they developed their students' metacognition in their course. I was unsurprised to hear that many of these instructors' suggestions for metacognition development actually focused on cognition, because many undergraduate instructors are not required to learn about educational psychology concepts. This may imply that to improve metacognition development in chemistry education, awareness about the importance of metacognition and training on how to implement it in chemistry classes is necessary, and these changes will be most sustainable if they happen at a departmental level (Reinholz, et al., 2019). I also realized the importance of activities that implicitly prompt students' metacognition and that could be easily incorporated into existing lesson plans. Fortunately, many of these activities already exist (Bowen et al., 2018; Casselman & Atwood, 2017; Fishovitz et al., 2020; Kadioglu-Akbulut & Uzuntiryaki-Kondakci, 2021; Sandi-Urena et al., 2012; Ye et al., 2020; Young et al., 2019). The goal of my second project was to investigate a series of questions that could serve as an activity for implicitly prompting students' metacognition.

In my second study, I found that biochemistry students do use metacognition while solving buffer problems. I observed all types of metacognitive knowledge and metacognitive skills in the twenty-five interviews, though every type was not present in each individual interview. Students most commonly employed their declarative knowledge and monitoring while working through the problems. I also observed an interesting trend while comparing the metacognition demonstrated in an interview against students' scores on the buffer problems: students who scored in the middle ranges were demonstrating the most metacognition, not the students who were scoring the highest. I believe this is due to where a student's understanding of buffers was in their zone of proximal development (Vygotsky, 1978). If their understanding was beginning to mature, but had not fully developed yet, they were more likely to rely on their metacognitive knowledge and metacognitive skills to aid them in solving the problem. It was outside the scope of this study to investigate a possible relationship between students' metacognition and their zone of proximal development, but this could be an area for future research.

When I compared students' transcripts for the first question to the second, I found that the implicit metacognitive prompts I asked before the second question prompted students to more actively employ their evaluating skill. Students also responded to these prompts about an "other" student in the first person, indicating that they were thinking about their thinking. From this I concluded that these questions were successful in implicitly engaging students' metacognition. The format of the questions is not topic-specific, and thus these questions could be incorporated into existing activities or assignments, which would allow instructors to easily implement metacognition development for their students with a minimal time investment on the instructor's part.

In conclusion, for this dissertation I interviewed two main stakeholders in undergraduate education: instructors and students. Through these interviews, I was able to understand how instructors value and perceive metacognition development in their classrooms, and to develop an easy-to-implement activity that implicitly prompts students' metacognition.

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APPENDIX A

INSTRUCTOR STUDY EMAIL INVITATION

Subject: Invitation to Participate in Interview study

Message:

Dear Professor Example,

My name is Amber Heidbrink, I am a doctoral student in Chemical Education research at the University of Northern Colorado. I am writing to invite you to participate in an interview study, focusing on professors' teaching practices and classroom expectations. For the study, I would like to interview professors who teach general chemistry, organic chemistry, or biochemistry. The interview should last about 45 minutes to 1 hour. I know your time is valuable, and if you decide to participate, as compensation I would like to offer you a $20 Amazon gift card. Also, if you decide to participate, please select an exam type problem that you believe could best assess whether a student "got it" as far as the main material is concerned, and either send it to me before the interview, or bring a copy with you to the interview. (You may email materials to me at amber.heidbrink@unco.edu.)

If you would like to participate, please respond to this email and let me know. Also, if you have any questions about participating, I will be happy to answer them via email. I would like to schedule interviews in [city] sometime between [dates]. If you are traveling during this time and are unavailable but would still like to participate, I will have availability later in the summer, so please let me know of your interest.

Thank you for your time,

Amber Heidbrink, M.S.

Doctoral Student, Chemical Education

Department of Chemistry and Biochemistry

University of Northern Colorado

Greeley, CO 80639

APPENDIX B

INSTITUTIONAL REVIEW BOARD APPROVAL LETTER
FOR INSTRUCTOR STUDY

UNIVERSITY OF
NORTHERN COLORADO

Institutional Review Board

DATE:	March 22, 2018
TO:	Amber Heidbrink, M.S.
FROM:	University of Northern Colorado (UNCO) IRB
PROJECT TITLE:	[1204190-1] Professors' perspectives on metacognition development in their classrooms
SUBMISSION TYPE:	New Project
ACTION:	APPROVAL/VERIFICATION OF EXEMPT STATUS
DECISION DATE:	March 22, 2018
EXPIRATION DATE:	March 22, 2022

Thank you for your submission of New Project materials for this project. The University of Northern Colorado (UNCO) IRB approves this project and verifies its status as EXEMPT according to federal IRB regulations.

Amber,

It is great to see the progression of your research. Thanks for such a well-written request! Best,

Maria

We will retain a copy of this correspondence within our records for a duration of 4 years.

If you have any questions, please contact Sherry May at 970-351-1910 or Sherry.May@unco.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB's records.

APPENDIX C

INSTRUCTOR STUDY INTERVIEW PROTOCOL

Interview main questions:

- What are the main courses that you teach?
- What are all the courses you have taught?
- What do you intend the students to learn in this course? What do you see as the major focus of this course? (Why is it important for students to know this?)
- Describe your classroom environment (or describe an in-class activity, expectations of students in that activity)
- Please provide an exam type problem that you believe could best assess whether a student "got it" as far as the main material is concerned. In other words, if you were short of time and had to grade only part of the exam, which problems would best demonstrate that students do or don't get it?

  Now show me how you expect a proficient student to solve the problem.
- What knowledge or reasoning skills were you expecting students to demonstrate with this question?
- Would a partial answer to the test question tell you anything about the student? If so, what?
- If a student can't begin the question, what does that tell you they're lacking? (not used in all interviews)
- Describe the "ideal" college student/ What do students need to be able to do to be successful in your class?

  (How many (about what percentage) of your students meet these criteria?)

- ➢ Do you have a "class expectations" talk at the beginning of the semester? What are the main points of that talk? (not used in all interviews)
- ➢ Do you see a difference in students' study habits/skills depending on their age? Either traditional students vs. non-traditional students or lowerclassmen vs. upperclassmen?
- ➢ What level of self-efficacy would you say your students have? (How self-efficacious are they?) (not used in all interviews)
- ➢ Do you expect students to be self-motivated and self-regulatory in their learning? If so, what does a self-motivated and self-regulated student look like to you?
- ➢ Do you see these abilities in your students?
- ➢ Do you remember how you developed the ability to self-regulate your learning? When do you feel like you took ownership of your own education? Was there anything in particular that you did, or that changed for you?

  (Was there ever a time when you realized your study habits were not as good as you thought they were? What did you do to change?)

One of my goals in this study is to discern professors' perspectives on metacognition

- ✓ Are you familiar with the term?
- ✓ How would you define metacognition? (thinking about thinking, metacognitive knowledge= knowing what you know/don't know, metacognitive skills= planning, monitoring, evaluating)
- ✓ How would you describe metacognitive skills?
- ✓ In what types of experiences/activities do you notice yourself using metacognitive skills?

- ✓ Are there any class activities, lab activities, or types of problems where you expect your students to have the ability to plan, monitor, and evaluate their progress/learning/understanding?
- ✓ Is it the professors' responsibility to teach students about metacognitive skills? Why or why not? If so, what does that look like?
- ✓ If not, how should students be learning these skills? Whose responsibility is it to teach them?
- ✓ Do you think metacognition is important? Why or why not?
- ✓ Do you do anything to specifically develop metacognitive skills in your students?
- ➢ How can we (chemistry instructors) improve the development of metacognition in chemistry students?
- ➢ What are some barriers that you have experienced to being able to develop metacognition in your students?

APPENDIX D

CONSENT FORM TO PARTICIPATE IN INSTRUCTOR STUDY INTERVIEWS

CONSENT FORM FOR HUMAN PARTICIPANTS IN RESEARCH

UNIVERSITY OF NORTHERN COLORADO

Project Title: Professors' perspectives on metacognition development in their classrooms

Doctoral Student Researcher: Amber Heidbrink, M.S.

email: amber.heidbrink@unco.edu

Research Advisor: Melissa Weinrich, PhD

phone number: (970)351-1172

email: melissa.weinrich@unco.edu

The goal of this research project is to gain insight on professors' teaching practices and classroom expectations. As a participant in this study, you will be asked to participate in an interview lasting approximately 45 minutes-1 hour. The interview will be transcribed and analyzed.

Steps will be taken to maximize confidentiality during the course of data collection and analysis. Signed consent forms will be stored separately from the data so that names cannot be linked to the information collected. Each participant will be assigned a pseudonym for confidentiality and data analysis purposes. Only this pseudonym will be associated with your answers to questions and your basic demographic information. Voice recording will be stored on password protected devices. Transcripts will be de-identified and pseudonyms used in all publications.

I believe there isn't any risk to being in this study. I do not expect you to encounter risk other than what occurs in a normal day. I know your time is valuable, and it will cost you 45 minutes-1 hour of your time to interview with me. As compensation for your time, you will be given a $20 gift card.

Participation is voluntary. You may decide not to participate in this study and if you begin participation you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. Having read the above and having had an opportunity to ask any questions, please sign below if you would like to participate in this research. A copy of this form will be given to you to retain for future reference. If you have any concerns about your selection or treatment as a research participant, please contact the Office of Sponsored Programs, 25 Kepner Hall, University of Northern Colorado Greeley, CO 80639; 970-351-1910.

______________________________________   _______________________________________

Participant's Signature   Date   Researcher's Signature   Date

APPENDIX E

INSTRUCTOR DEMOGRAPHIC FORM

Demographics:

Please select your age range:

18-24 25-34 35-44 45-54 55-64 65+

What is your gender? _____________

Please select the ethnicity that best describes you:

White

Hispanic or Latino

Black or African American

Native American or American Indian Asian/Pacific Islander

Other (Please specify) _______________

What is the highest level of education you have received?

Bachelor's degree

Master's degree

Professional degree

Doctorate

Which of the following best describes your position at the university?

Adjunct/part-time faculty

non-Tenure track faculty

Tenure-Track faculty

Tenured faculty

professor Emeritus

At which type of university are you currently employed?

R1

R2

masters granting

primarily undergraduate institution

community college

other: specify_________________

At which type(s) of universities have you ever been employed?

R1

R2

masters granting

primarily undergraduate institution

community college

other: specify_________________

How long have you been teaching chemistry?

0-5 years 6-10 years 11-15 years 16-20 years 21-25 years

APPENDIX F

APPROACHES TO TEACHING INVENTORY SURVEY ITEMS

All survey items have five possible responses and will be scored on a five-point scale: (1) Rarely or never true, (2) sometimes true, (3) true about half the time, (4) frequently true, (5) almost always or always true.

1) I design my teaching in this subject with the assumption that most of the students have very little useful knowledge of the topics to be covered.
2) I feel it is important that this subject should be completely described in terms of specific objectives relating to what students have to know for formal assessment items.
3) In my interactions with students in this subject I try to develop a conversation with them about topics we are studying.
4) I feel it is important to present a lot of facts to students so that they know what they have to learn for this subject.
5) I feel that the assessment in this subject should be an opportunity for students to reveal their changed conceptual understanding of the subject.
6) I set aside some teaching time so that the students can discuss, among themselves, the difficulties that they encounter studying this subject.
7) In this subject I concentrate in covering the information that might be available from a good textbook.
8) I encourage students to restructure their existing knowledge in terms of the new way of thinking about the subject that they will develop.
9) In teaching sessions for this subject, I use difficult or undefined examples to provoke debate.
10) I structure this subject to help students to pass the formal assessment items.

11) I think an important reason for running teaching sessions in this subject is to give students a good set of notes.

12) When I give this subject, I only provide the students with the information they will need to pass the formal assessments.

13) I feel that I should know the answers to any questions that students may put to me during this subject.

14) I make available opportunities for students in this subject to discuss their changing understanding of the subject.

15) I feel that it is better for students in this subject to generate their own notes rather than always copy mine.

16) I feel a lot of teaching time in this subject should be used to question students' ideas.

APPENDIX G

INSTITUTIONAL REVIEW BOARD APPROVAL LETTER FOR APPROACHES TO TEACHING INVENTORY SURVEY AMENDMENT

UNIVERSITY OF
NORTHERN COLORADO

Institutional Review Board

DATE:	June 5, 2019
TO:	Amber Heidbrink, M.S.
FROM:	University of Northern Colorado (UNCO) IRB
PROJECT TITLE:	[1204190-2] Professors' perspectives on metacognition development in their classrooms
SUBMISSION TYPE:	Amendment/Modification
ACTION:	MODIFICATION APPROVED/VERIFICATION OF EXEMPT
STATUS DECISION DATE:	June 5, 2019
EXPIRATION DATE:	March 22, 2022

Thank you for your submission of Amendment/Modification materials for this project. The University of Northern Colorado (UNCO) IRB approves this project modification and verifies its continued status as EXEMPT according to federal IRB regulations.

The modifications requested to include a follow up survey have beenapproved. Thank

you and best of luck as you continue your research!

Nicole Morse,

Research Compliance Manager

We will retain a copy of this correspondence within our records for a duration of 4 years.

If you have any questions, please contact Nicole Morse at 970-351-1910 or nicole.morse@unco.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB's records.

APPENDIX H

CONSENT FORM TO COLLECT APPROACHES TO TEACHING INVENTORY SURVEY DATA

CONSENT FORM FOR HUMAN PARTICIPANTS IN RESEARCH

UNIVERSITY OF NORTHERN COLORADO

Project Title: Professors' perspectives on metacognition development in their classrooms

Doctoral Student Researcher: Amber Heidbrink, M.S.

email: amber.heidbrink@unco.edu

Research Advisor: Melissa Weinrich, PhD

phone number: (970)351-1172

email: melissa.weinrich@unco.edu

The goal of this research project is to gain insight on professors' teaching practices and classroom expectations. For this phase of this research project, you will be asked to complete the Approaches to Teaching Inventory, a survey that measures instructors' thoughts and perspectives of teaching.

Steps will be taken to maximize confidentiality during the course of data collection and analysis. Each participant will be assigned a pseudonym for confidentiality and data analysis purposes.

Only this pseudonym will be associated with your answers to the survey items. Pseudonyms will be used in all publications.

I believe there isn't any risk to being in this study. I do not expect you to encounter risk other than what occurs in a normal day. I know your time is valuable, and it will cost you 5-10 minutes of your time to complete the survey. Please email Amber at amber.heidbrink@unco.edu with any questions you may have about completing the survey.

Participation is voluntary. You may decide not to participate in this study and if you begin participation you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. Having read the above and having had an opportunity to ask any questions, please indicate below if you would like to participate in this research. If you have any concerns about your selection or treatment as a research participant, please contact the Office of Sponsored Programs, 25 Kepner Hall, University of Northern Colorado Greeley, CO 80639; 970-351-1910.

By selecting "Continue to Survey" below, you affirm that you consent to participate and allow your responses to the survey being collected and analyzed for the purpose of this study. If you do not consent to participating, please select "Exit Survey" below.

-Continue to Survey

-Exit Survey

APPENDIX I

INSTITUTIONAL REVIEW BOARD APPROVAL LETTER FOR STUDENT STUDY

UNIVERSITY OF
NORTHERN COLORADO

Institutional Review Board

DATE:	September 10, 2019
TO:	Amber Heidbrink, M.S.
FROM:	University of Northern Colorado (UNCO) IRB
PROJECT TITLE:	[1474904-1] Investigating biochemistry students' metacognition while solving buffer problems
SUBMISSION TYPE:	New Project
ACTION:	APPROVAL/VERIFICATION OF EXEMPT
STATUS DECISION DATE:	September 10, 2019
EXPIRATION DATE:	September 10, 2023

Thank you for your submission of New Project materials for this project. The University of Northern Colorado (UNCO) IRB approves this project and verifies its status as EXEMPT according to federal IRB regulations.

We will retain a copy of this correspondence within our records for a duration of 4 years.

If you have any questions, please contact Nicole Morse at 970-351-1910 or nicole.morse@unco.edu. Please include your project title and reference number in all correspondence with this committee.

This letter has been electronically signed in accordance with all applicable regulations, and a copy is retained within University of Northern Colorado (UNCO) IRB's records.

APPENDIX J

EMAIL INVITATION TO STUDENTS TO PARTICIPATE IN INTERVIEW STUDY

Subject: Interview sign up

Message:

Dear [Student],

Thank you for your interest in participating in my interview study! To sign up for a time, please click the link below, which will take you to a doodle poll with available times for your interview. Please include your first and last name when you sign up. In the Doodle poll, you can choose to view the options in "list" view or "calendar" view. "Calendar" view will show you all the options in a week's time period.

https://doodle.com/poll/uakir69dkkdy242w

I will send you a reminder email with the time and location of your interview one day before your interview. We will meet in Ross 3620 (chemistry third floor of Ross, in the lab hallway, right across from the stockroom window).

If you cannot meet at any of the available times, please send me an email and we will work out a time.

Please send any questions or concerns to Amber at amber.heidbrink@unco.edu

Thank you again for participating!

Best,

Amber Heidbrink, M.S.

Doctoral Candidate, Chemistry Education

Department of Chemistry and Biochemistry

University of Northern Colorado

Greeley, CO 80639

APPENDIX K

CONSENT FORM FOR STUDENT STUDY

CONSENT FORM FOR HUMAN PARTICIPANTS IN RESEARCH

UNIVERSITY OF NORTHERN COLORADO

Project Title: Investigating biochemistry students' metacognition while solving buffer problems

Doctoral Student Researcher: Amber Heidbrink, M.S.

email: amber.heidbrink@unco.edu

Research Advisor: Melissa Weinrich, PhD

phone number: (970)351-1172

email: melissa.weinrich@unco.edu

The goal of this project is to understand chemistry students' use of metacognition and thought processes while working through chemistry problems. As a participant in this study, you will be asked to be interviewed. The interview will last about 45 minutes—1 hour. The interview will be recorded and later transcribed. At the end of the interview, you will be asked to complete the Revised Study Process Questionnaire, which will ask you questions about your approaches to studying. You will also be asked to provide basic demographic information. By consenting to participate in this study **you give permission for your first exam grade to be provided to the researcher from your course instructor.**

Steps will be taken to maximize confidentiality during data collection and analysis. Signed consent forms will be stored separately from the data so that names cannot be linked to the information collected. Each participant will be assigned a pseudonym for confidentiality and data analysis purposes. Only this pseudonym will be associated with your answers to questions, survey items, and your basic demographic information. Voice recording will be stored on password protected devices. Transcripts will be de-identified and pseudonyms used in all publications.

While participating in this study, I do not expect you to encounter risk other than what occurs in a normal day. I know your time is valuable, and it will cost you 45 minutes-1 hour of your time to interview with me. As compensation for your time, you will be given a small amount of extra credit.

Participation is voluntary. You may decide not to participate in this study and if you begin participation you may still decide to stop and withdraw at any time. Your decision will be respected and will not result in loss of benefits to which you are otherwise entitled. Having read the above and having had an opportunity to ask any questions, please sign below if you would like to participate in this research. A copy of this form will be given to you to retain for future reference. If you have any concerns about your selection or treatment as a research participant, please contact the Office of Sponsored Programs, 25 Kepner Hall, University of Northern Colorado Greeley, CO 80639; 970-351-1910.

____________________________________ ____________________________________

Participant’s Signature Date Researcher’s Signature Date

APPENDIX L

REVISED STUDY PROCESS QUESTIONNAIRE SURVEY ITEMS

This survey is from the publication: Biggs, J., Kember, D., & Leung, D. Y. P. (2001). The revised two-factor Study Process Questionnaire: R-SPQ-2F. British Journal of Educational Psychology, 71(1), 133–149. https://doi.org/10.1348/000709901158433

Revised Study Process Questionnaire (R-SPQ-2F)

This questionnaire has a number of questions about your attitudes towards your studies and your usual way of studying.

There is no *right* way of studying. It depends on what suits your own style and the course you are studying. It is accordingly important that you answer each question as honestly as you can. Please fill in the appropriate circle alongside the question number on the answer sheet. The letters alongside each number stand for the following response:

A—this item is *never* or *only rarely* true of me

B—this item is *sometimes* true of me

C—this item is true of me about *half the time*

D—this item is *frequently* true of me

E—this item is *always* or *almost always* true of me

Please choose the *one* most appropriate response to each question. Fill the oval on the answer sheet that best fits your immediate reaction. Do not spend a long time on each item: your first reaction is probably the best one. Please answer each item.

Do not worry about projecting a good image. Your answers are CONFIDENTIAL.

Thank you for your cooperation.

Possible Answers:

A: *Never* or *rarely* true **B:** *sometimes* true **C:** true about *half the time* **D:** *frequently* true

E: *always/almost always* true

1. I find that at times studying gives me a feeling of deep personal satisfaction.
2. I find that I have to do enough work on a topic so that I can form my own conclusions before I am satisfied.
3. My aim is to pass the course while doing as little work as possible.
4. I only study seriously what's given out in class or in the course outlines.
5. I feel that virtually any topic can be highly interesting once I get into it.
6. I find most new topics interesting and often spend extra time trying to obtain more information about them.
7. I do not find my course very interesting so I keep my work to the minimum.
8. I learn some things by rote, going over and over them until I know them by heart even if I do not understand them.
9. I find that studying academic topics can at times be as exciting as a good novel or movie.
10. I test myself on important topics until I understand them completely.
11. I find I can get by in most assessments by memorizing key sections rather than trying to understand them.
12. I generally restrict my study to what is specifically set as I think it is unnecessary to do anything extra.
13. I work hard at my studies because I find the material interesting.
14. I spend a lot of my free time finding out more about interesting topics which have been discussed in different classes.

15. I find it is not helpful to study topics in depth. It confuses and wastes time, when all you need is a passing acquaintance with topics.
16. I believe that lecturers shouldn't expect students to spend significant amounts of time studying material everyone knows won't be examined.
17. I come to most classes with questions in mind that I want answering.
18. I make a point of looking at most of the suggested readings that go with the lectures.
19. I see no point in learning material which is not likely to be in the examination.
20. I find the best way to pass examinations is to try to remember answers to likely questions.

APPENDIX M

STUDENT STUDY INTERVIEW PROTOCOL

Part A: Student solves buffer problem with only the following prompt, and some possible probing.

Introduction:

For this research project, I am very interested in how biochemistry students think about buffer problems. I want to know what is going through your mind throughout the entire process of solving this problem, from when you first look at it. I'm not concerned with the "correctness" of your final answer, so if you don't feel confident about your answer or your process, that's fine—great actually! For this project, I want to talk with students from all levels of understanding, so no matter where you're at, your perspective is valuable. So it will help me out a lot if you can just voice exactly what you're thinking, even if it's kind of stream of consciousness.

Questions:

Please solve the following problem. While working through the problem, talk me through what you are doing and thinking.

<u>Possible Probing questions, to be asked after the student completes the problem:</u>

How did you know to set up _____ this way?

You said ________, what does that mean, or can you tell me more about that?

What does this (symbol, word, notation) mean?

What do you notice about the problem?

Can you tell me more about ____?

Is there anything else you would like to say?

Part B: Implicit prompting toward metacognition

What is a way of thinking about this problem that might lead a student astray?

Follow-up: Why do you think a student would do that?

Follow-up/subquestion 1: Can you describe how a student who “does not carefully reflect on what the question is asking” might work through the problem? (Talanquer, 2017, p.1807)

Subquestion 2: Can you describe how a student who is “misguided by their intuition” might think about and answer this problem? (Talanquer, 2017, p.1807)

Is there something specific about buffer problems that would cause someone to mess up their solution to this question?

Follow-up: Why is [__] confusing?

What would that student miss in this problem? What would they get right?

Follow-up: Why do you think that?

Now please try and solve the problem, while thinking aloud.

[After student completes work on problem] Do you have any new ideas about how a student might be led astray, after working on the problem yourself?

APPENDIX N

STUDENT DEMOGRAPHIC FORM

Student Demographic Form

Gender: _______

Age:________

Please select the ethnicity that best describes you (Select all that apply):

White	Native American or American Indian
Hispanic or Latino	Asian/Pacific Islander
Black or African American	Other:_____________

What is your major?

____

Please list the course names for all other chemistry and biology courses you have taken thus far in your undergraduate studies:

What year in school are you?

Freshmen Sophomore Junior Senior Other

APPENDIX O

GRADING RUBRIC FOR BUFFER PROBLEMS

Buffer design: Buffers can be prepared by directly combining the acid/base conjugate pair or by inducing reactions that generate them in solution. Imagine that you wanted to prepare a buffer containing equal concentrations of HNO_2 and NO_2^-. These are the substances you have available to complete your task: H_2O, HNO_2, KNO_2, HCl, NaOH. Propose three different strategies to prepare the targeted buffer. Justify your reasoning.

Comments about rubric: Unfortunately, none of the twenty-five students responded with a completely correct answer for this question. Thus, the students who earned a “3” were the best responses present in the sample, but they were not 100% correct. What the students wrote and said while working through this problem were both taken into account for assessment.

3: Responses that earned a 3 were able to provide 3 equations that represented a potential HNO2/NO2- buffer system. This means HNO2 and NO2- had to both be present in the equation, with one on the reactant side and one on the product side. The equations did not need to be perfect--there were responses in this category that left out spectator ions. They also did not need to address the "equal concentrations" portion of the question, since there was no response that took that into account, other than to say, "I don't know how to do that." No responses where the student added strong base or acid over the arrow were included in this category--that type of addition to a response automatically disqualified that equation, because addition of strong acid or strong base over the arrow would affect (and in most cases prevent) the formation of the buffer. The “3” responses also did not necessarily discuss their reasoning for why they thought the 3 reactions they provided would make a buffer, because very few of the students provided that sort of discussion while solving the problem. [Almost all the students ignored the "Justify your reasoning" portion of the question too.]

2: Responses that earned a 2 had two reactions that met all the same criteria as was required of "3" responses. The only difference was they only provided 2 reactions instead of 3.

1: Responses that earned a 1 were only able to provide one reaction that met the same criteria as the "2" and "3".

0: Responses that earned a 0 were unable to provide any reactions that could produce the HNO2/NO2- buffer system.

Buffer pH: Imagine that you use 0.6 moles of HCN (pKa = 9.2) and 0.5 moles of NaCN to prepare two different buffer solutions. In one case you add these amounts to a beaker with 100 mL of H_2O. In the other case, you add the same amounts to another beaker with 200 mL of H_2O. Which of the two buffer solutions will have a lower pH? Clearly justify your reasoning.

Comments about rubric: Many students seemed to be more familiar with what this question was asking them to do, and were able to remember the Henderson-Hasselbalch equation to aid in their solution of the problem. While conducting the interviews, the only resource I provided the students was a calculator, and I quickly realized that many of the students knew of the existence of the Henderson-Hasselbalch equation but could not perfectly recall it from memory. I tried to act as a search engine for the students, by asking them what they would look up online or in their textbook to find the correct equation, and so was able to provide many of them with the equation if they could not remember it. However, I usually did not offer students to be their textbook/search engine unless they stated they knew there was an equation they could use, and that they were completely stuck without the equation. What the students wrote and said while working through this problem were both taken into account for assessment.

3: A score of 3 arrived at the correct answer, which was that the two solutions have the same pH. Only one of the 6 in this category could provide any reasoning for why.

2: A score of 2 displayed good reasoning for their answer but did not get the correct answer. All of these students made assumptions about the solutions' pH--that it was acidic or basic, and thus chose the lower pH based on which solution was more concentrated (if acidic) or dilute (if basic). If they thought the HCN/NaCN buffer was naturally acidic, they chose the 100mL beaker to have the lower pH. If they thought the HCN/NaCN buffer was naturally basic, they chose the 200mL beaker to have the lower pH, because it would be more dilute.

1: The majority of the students with a score of 1 mis-interpreted the question and believed the HCN and NaCN were in separate beakers, and thus chose the HCN as the one with the lower pH. One participant correctly interpreted the question, and correctly identified that they needed to use the H-H equation, but displayed a LOT of misconceptions and incorrect understanding, incorrectly used the H-H equation, and therefore did not arrive at the correct answer.

0: Students who received a score of zero did not have anything coherent to say about the problem. They had little to no understanding of pKa, pH, acids and bases, and many of them did not realize the problem was asking them to make a buffer solution.

APPENDIX P

STUDENT STUDY CODEBOOK

Table P.1

Student Study Codebook, Metacognition definitions according to Zohar and Dori (2012)

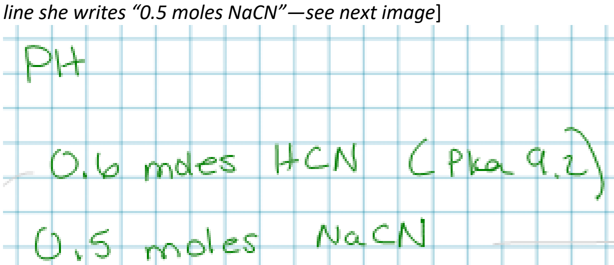
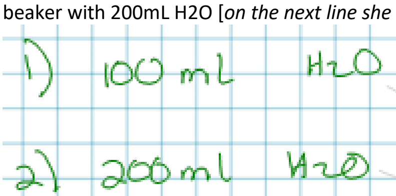
Example quote	Explanation
Metacognitive Knowledge	
Declarative knowledge: "Knowledge about one's skills, intellectual resources, and abilities as a learner"	
"I don't even know how a buffer is related to pH to be honest. You just always hear buffer pH and all I focus on is the pH not the actual buffer part of it." (Participant 3)	In this quote, Participant 3 discusses that she knows that she does not know how buffers are related to pH.
Conditional knowledge: "Knowledge about when and why to use learning procedures"	
"Oh, typically. Um, if I'm not exactly sure what to do, yeah. A lot of times I try to like go through, okay. Like how do I break this down so it makes sense in my mind? So I actually can like translate the, like all the words over, it's more like a meaningful concept in my mind I guess. Because sometimes I'll look at like what the problem says and it just won't have a lot of meaning. I'm like, okay, I see pKa, I see the numbers, I see moles, I see that I have two different beakers, but like what am I actually doing? And so sometimes I have to just like try to visualize what actually is going on and then apply whatever knowledge to whatever I'm visualizing." (Participant 21)	This is an example of Participant 21's conditional knowledge. She knows when she is unsure what to do for a problem to activate these questions and processes to clarify what she needs to do to answer the question. The condition is "I'm not exactly sure what to do", and this tells her it is appropriate to activated procedural knowledge about how to dig deeper into the question and better understand how to solve it.
Procedural knowledge: "Knowledge about how to implement learning procedures (e.g., strategies)"	
"So, I always try to look at my numbers first and then I write those down to see okay what kinda like, I call them like hard evidence, like do I have that I could calculate something with. And, then it's really like, "okay, let's look at the fluff, like the words in between and see what I could do with those numbers. Like what like how am I trying to use those? What ways can I manipulate those to get the correct answer?" But I always try to start with my numbers and write down what I have. Like just straight up because it helps condense it when I have those numbers, so I'm like okay now I can really pick through all the words and see what I'm trying to look for. So, that's how I approach it." (Participant 11)	Participant 11 describes her procedural knowledge for the learning procedure she has for picking apart questions to decipher all the provided information and use it to develop a plan to solve the problem.
Metacognitive Skills	
Planning: "Planning, goal setting, and allocating resources prior to learning"	
"Okay, so looking for, it's okay if I, I'll just write on this. Which of the two solutions will have a lower pH? So I'm looking for pH [*writes "pH"*] and I know that I have 0.6 moles of HCN with pKa 9.2. 0.5 moles NaCN [*on a new line she writes "0.6 moles HCN (pKa 9.2)", and then on the next line she writes "0.5 moles NaCN"—see next image*]  ... [mumbling] with 100mL H2O [*on a new line, she writes "1) 100 mL H2O"*] and in the other case I add amounts to a beaker with 200mL H2O [*on the next line she writes "2) 200 mL H2O"—see next image*]  " (Participant 21)	Participant 21 uses planning to allocate resources (when she writes down the important information from the question) and to set her goal for answering the question when she says "So I'm looking for pH".

Table P.1 Continued

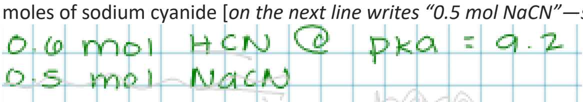
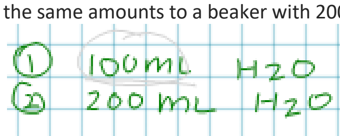
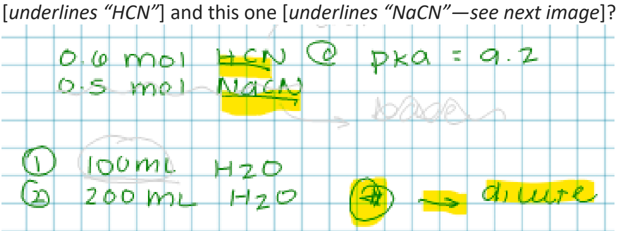
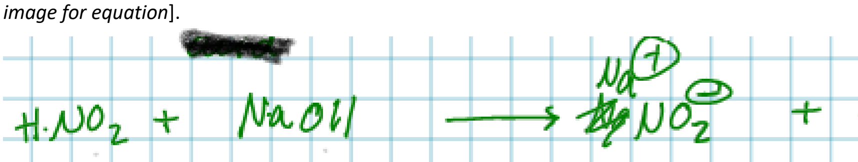
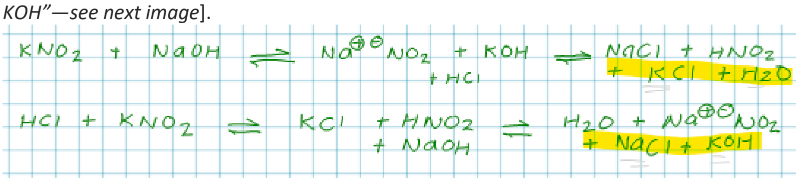
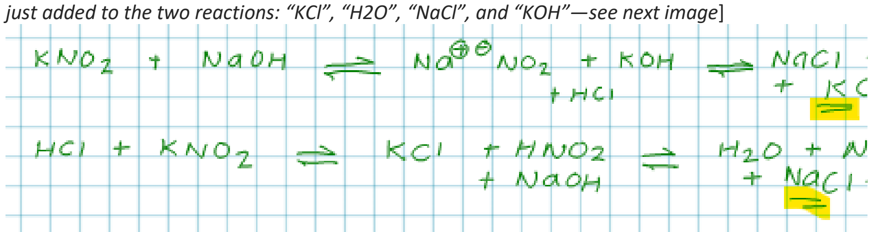
Metacognitive Skills	
Example quote	**Explanation**
Information Management: “Skills and strategy sequences used on-line to process information more efficiently”	
“So, I have 0.6 moles of HCN at pKa is 9.2 [*writes “0.6 mol HCN @ pKa = 9.2”*], and then, 0.5 moles of sodium cyanide [*on the next line writes “0.5 mol NaCN”—see next image*].  And different, okay. Okay, in one of these cases we have some case 1 we have 100 mL of H2O [*writes “1) 100mL H2O”*] and in the other case, you add the same amounts to a beaker with 200 mL of H2O [*writes “2) 200mL*  *H2O”—see next image*]. Okay, right off the bat, I know this [*draws a star next to “2) 200mL H2O”*] has more water in it, so that's gonna be more dilute [*draws an arrow pointing away from the star next to “2) 200mL H2O” and writes “dilute”*] . And, then, I have 100, okay. So, which of the two buffer solutions, so is it asking between this one [*underlines “HCN”*] and this one [*underlines “NaCN”—see next image*]?  Yes?” (Participant 11)	Participant 11 uses her information management skill to organize the information given in the problem, so that she can process it more efficiently.
Monitoring: “Ongoing appraisal of one’s learning or strategy use”	
“So looking I could maybe do the H2O on this side and NaOH on this side [*on the same equation, after “NO2- +” she writes “H2O” and then returns to the other side of the equation and after “HNO2 +” writes “NaOH”*]. Yeah, 'cause then that would, yeah, that was right [*on the product side, she writes “Na” in front of “NO2-“, crosses “Na” out, and then writes “Na+” above it—see image for equation*].  'Cause that would be one plus to one minus the OH would get this H and become H2O which is usually a byproduct so that seems right. Um, so I think that that could work to be, I dunno if that's considered a buffer system 'cause I think they're supposed to be something in the middle. But um... which it gave it to me...I don't know.” (Participant 17)	While working through the Buffer design problem, Participant 17 writes out a possible equation for a buffer system and then makes an appraisal of her work, and decides that it could be a solution, though she is not 100% certain.

Table P.1 Continued

Metacognitive Skills	
Example quote	**Explanation**
Debugging: "Strategies used during learning to correct comprehension and performance errors"	
"Well, okay. They were much more difficult because I'm like, "Oh, um. I'm kind of in this intermediate phase where I'm like I have one thing that I know I want, and I know I can react it with something to get the other thing that I know I want". But, I'm, I have this piece of information, so like in the second one, that KOH, I'm like, "Okay, if I add in hydrochloric acid, I know some of that's gonna like react with", I guess I could write that as another product 'cause I guess some of it would react, so you'd get KCl and some more water [*on the second reaction, in the product section furthest to the right after "NaCl + HNO2" she writes "+ KCl + H2O"*]. And, down here, it's kind of the same thing where I would get some NaCl plus KOH [*on the third reaction, in the product section furthest to the right she writes after "H2O + Na+ NO2-" "+ NaCl + KOH"—see next image*].  Oh, so I'm thinking I might get some other byproducts in these guys [*underlines the 4 substances she just added to the two reactions: "KCl", "H2O", "NaCl", and "KOH"—see next image*]  that aren't necessarily what I was trying to form, but they are gonna form as a result of having to do an extra little step there." (Participant 11)	While reviewing the equations she wrote out for the Buffer Design question, Participant 11 finds some mistakes in her equations, and adds information to fix those mistakes. By adding the highlighted information, she corrects the identified "performance errors", which is how she uses "debugging".
Evaluation: "Analysis of performance and strategy effectiveness after a learning episode"	
"So I got the same answer for both solutions. [pause] And that, I mean, to me that makes sense because if you put it in water, both of these solutions are gonna dissociate, um, fully. So it would make sense that it would kind of have a one to one ratio between what you put in and what's dissociating in solution. So yeah, it makes sense that it would be the same pH for both of them and the volume of the water wouldn't change what, um, I guess the pH of the solution." (Participant 23)	After arriving at an answer, Participant 23 takes a moment to evaluate whether his answer is feasible. After considering his knowledge about buffer systems he decides that his answer is reasonable.