# How Drawing Prompts Can Help Students Learn Visual-Spatial Content in Science, Technology, Engineering, and Mathematics (STEM)

By

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A dissertation submitted in partial fulfillment of the requirements for the degree of

Doctor of Philosophy

in

Educational Psychology

at the

University of Wisconsin-Madison

2019

Date of Final Oral Examination: 05/09/2019

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# Abstract

Professionals in science, technology, engineering, and mathematics (STEM) often *draw* to explore and communicate visual-spatial concepts. However, novice undergraduate students who plan to pursue STEM careers seldom draw to learn content. To address this issue, I investigated the effects of implementing *drawing prompts* that ask students to draw visual-spatial STEM content. I first reviewed the literature and developed a theoretical framework that synthesizes six distinct learning processes from prior work within the cognitive and sociocultural perspectives. Because prior work has primarily investigated these processes in separate lines of work, I tested this framework in four studies that combine multiple learning processes across theoretical perspectives. Study 1 tested drawing prompts that target multiple learning processes from the cognitive perspective in a laboratory experiment and showed that such prompts can help students learn content effectively and efficiently. Study 2 investigated drawing prompts for sociocultural processes in a chemistry course and showed that they were not effective, when compared to prompts for another disciplinary practice and a business-as-usual condition. The instructors did not recognize students' difficulties when drawing and thus may not sufficiently provide support to help students engage with their drawings. To address this issue, Study 3 implemented drawing prompts that support multiple learning processes across cognitive and sociocultural perspectives, which were effective in enhancing students' conceptual understanding in a semester-long electrical engineering course. Results also showed that students did not engage with drawings in line with disciplinary practices as used by professionals. To help students engage in disciplinary practices, Study 4 found that drawing prompts that support both cognitive and sociocultural processes were more effective than those that support only sociocultural processes. Overall, results suggest that students may require drawing prompts that combine learning processes across cognitive and sociocultural perspectives to engage with drawings and learn content in STEM classrooms.

# Acknowledgements

This dissertation is only made possible by the support of many who have encouraged, sustained, carried, and pushed me throughout this process. A special thank you to my advisor, Martina Rau, who has made my graduate career possible through her quick, insightful, and accessible guidance on all of my work. I am grateful for the incredible amount of time and energy she lent to helping me develop as the scholar I am today.

I thank my committee members, Martina Rau, Martha Alibali, Matthew Berland, Dan Bolt, and Mitch Nathan, for their advice, feedback, and enthusiasm on my dissertation work. Further, I thank the instructors, teaching assistants, and students who have participated in my studies and made this research possible. Importantly, I thank organizations that have funded my research, particularly the Wisconsin Center for Education Research, Graduate School, and the Institute of Education Sciences, U.S. Department of Education through Award #R305B150003 to the University of Wisconsin-Madison. The opinions expressed in this dissertation are my own and do not represent views of the U.S. Department of Education.

Further, I want to recognize my undergraduate research assistants who supported my research projects and to whom I owe much of my progress: Monali Adhikari, Lauren Altman, Greyson Bahr, Kyle Byrnes, Youn Ku (Q) Choi, Maggie Cram, Jainaba Corr, Kim Drastal, Roman Fabry, Natalie Fay, Molli Gering, Cassidy Hartzog, Ashley Hong, Luke Hou, Nick Hougstad, Injeong Jeon, Jing Jin, Navneet Kaur, Amber Kim, Saige Lacognata, Aubrey Lawson, Ashley Lee, Marguerite Lee, Tae Ho Lee, Maddy Lippman, Corey Little, Jenna Lustig, Ellen Lundquist, Zainab Manzoor, Louis Monette, Michael Seowon Mun, Lauren Pelletier, Aditi Renganathan, Maggie Reske, Peter Van Sandt, Bryan Sattler, Brenna Schneider, Jamie Schubert, Mike Schwanke, Cora Sheldon, Natalie Statz, Eda Tee, Yaa Tutu, Mackenzie Van Lanen, Manya Waldia, Julie Wallin, Krista Washechek, Haengjung Ye, and Kristen Younan.

In addition, I thank my network of fellow students, professors, and friends at the University of Wisconsin-Madison that contributed to my success. First, I am grateful for my cohort and members of my lab who have helped me with data, writing, and provided social support when needed. Particularly, I thank Tiffany Herder for always listening and helping with many rounds of IRR coding. Further, as the first member of my lab, I thank the "seniors" from other labs who have taken time to advise me along the way: Gol Arastoopour Irgens, Joe Michaelis, Libby Pier, Julia Rutledge, and Amanda Siebert-Evenstone. I would also like to thank the staff of the Educational Psychology Department and the Writing Center for all of their help.

I want to thank those who believed in me and supported me prior to and throughout my PhD career. In particular, I thank mentors from Haverford and Bryn Mawr Colleges: Marilyn Boltz, Joshua Brooks, Alison Cook-Sather, Howard Glasser, Barbara Hall, and Alice Lesnick. I also thank my supervisors and managers who served as my mentors, especially Diane Wacker, Claire Dragon, Lauren Bozzi, Linda Caswell, Alyssa Martinez, and Sarah Sahni.

Last but not least, I thank those who make my life brighter each and every day. First, I thank my heroes, my parents （伍日兴，李燕萍）who never got the chance to go to college themselves, but set me up with good life habits and provide a never-ending supply of food. I also thank my best friend, Stephanie Cheng, who always has the right words and responses for any situation and has walked me through the best and worst of times. Finally, I thank my partner, Christian Geske, for his encouragement, strength, and love, which has made the end of my PhD and my life immeasurably more fun and fulfilling.

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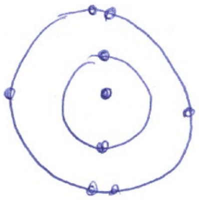
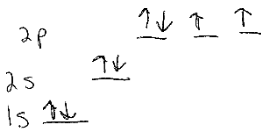
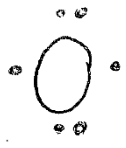
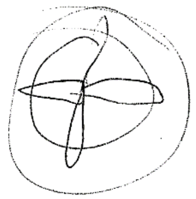
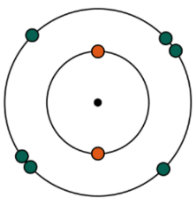
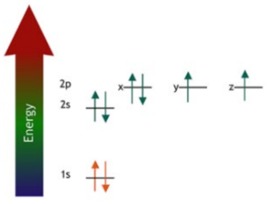
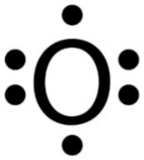
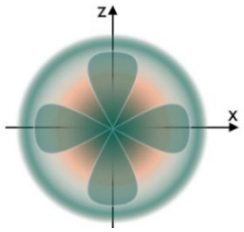
# Chapter 1

## Introduction

Professionals in science, technology, engineering, and mathematics (STEM) often *draw* to explore and communicate visual-spatial concepts (Arcavi, 2003; Goldschmidt, 1994). For instance, a chemist may draw visual representations of atoms on paper, as shown at the top of Table 1.1, to reason about bonding behavior or to discuss bonding with a colleague. Drawing can serve as a *cognitive* tool that helps STEM professionals make sense of concepts and revise their mental models to align with new information (Fish & Scrivener, 2007; Goldschmidt, 2003). In addition, drawing serves as a *sociocultural* tool that helps professionals communicate ideas with others and situate their work, especially in the context of other disciplinary practices (e.g., manipulating physical models, applying quantitative formulas) and tools (e.g., technologies that visualize abstract concepts) (Arcavi, 2003; Jee et al., 2014; Johri, Roth, & Olds, 2013). The process of drawing plays a key role in the success of STEM professionals in their fields (Arcavi, 2003; Brew, Fava, & Kantrowitz, 2012). Thus, drawing is widely considered to be an important professional practice (Brew et al., 2012; National Research Council, 2012).

Table 1.1
*Four instructor-provided visual representations and student-constructed drawings of an oxygen atom: Bohr model, energy diagram, Lewis structure, and orbital diagram.*

| | **Bohr model** | **Energy diagram** | **Lewis structure** | **Orbital diagram** |
|---|---|---|---|---|
| **Drawings of oxygen** |  |  |  |  |
| **Visual representations of oxygen** |  |  |  |  |

To promote learning from a sociocultural perspective, STEM instructors may prompt students to draw visual-spatial content in STEM to engage in the practices of professionals (Ainsworth, Prain, & Tytler, 2011; Fan, 2015; Quillin & Thomas, 2015). Recently, researchers have argued for the inclusion of drawing in STEM classrooms alongside reading, writing, and speaking to better align instructional practices with professional practices (Ainsworth et al., 2011; Cheng & Gilbert, 2009; National Research Council, 2012). Traditionally, instructional practices in STEM have primarily focused on *providing* pre-generated visual-spatial representations to students. For instance, STEM instructors may provide the visual representations of atoms shown in the bottom of Table 1.1 to help students explore chemistry concepts. Instructors may also provide visuals to students using educational technologies, which have been shown to be particularly effective in helping students learn visual-spatial STEM content (Rau, Bowman, & Moore, 2017; Stieff, 2011).

From a cognitive perspective, instructors may prompt students to draw in order to help them develop strategies that help them *visually* engage with new content. Due to the traditional instructional practices, STEM students often learn to interpret and explain instructor-provided visuals (Cheng & Gilbert, 2009; Tippett, 2016). However, they seldom learn to draw their own visuals as professionals do (de Vere, Melles, & Kapoor, 2011; Quillin & Thomas, 2015; Uesaka & Manalo, 2012). When unprompted to use specific strategies, students tend to spontaneously rely on verbal strategies (e.g., making lists or outlines) (Fiorella & Mayer, 2017). However, verbal strategies may not help students learn visual-spatial content that depicts relations between features (e.g., spatial arrangement of chambers in a human heart), which can be difficult to explain verbally (Tversky, 2011). For such concepts, recent research recommends *prompting students to draw* instead (Bobek & Tversky, 2014; Leutner & Schmeck, 2014).

Drawing prompts are verbal or text-based instructions that engage students in a drawing activity. For instance, after reading a scientific text about how birds fly, a prompt can ask students to “Draw the wing of a bird.” They can be provided verbally by instructors or implemented in course materials (e.g., worksheets, exercises, technologies). Often, STEM instructors only implement drawing prompts during exams to test students’ understanding of content *after* instruction (Nyachwaya et al., 2011; Quillin & Thomas, 2015). However, because students rarely draw spontaneously to learn content (de Vere et al., 2011; Uesaka & Manalo, 2012), implementing drawing prompts *during* instruction may particularly help students engage more deeply with content and learn STEM content.

To investigate the potential effects of drawing prompts during instruction, I reviewed prior research on how drawing prompts can affect learning outcomes in Chapter 2 (Lobato, Hohensee, & Diamond, 2014; Tippett, 2016). My review identified separate lines of research that have investigated drawing prompts based on different theoretical perspectives (Davatzes, Gagnier, Resnick, & Shipley, 2018; Leutner & Schmeck, 2014; Prain & Tytler, 2012; Van Meter & Garner, 2005). For instance, drawing prompts based on cognitive research engage students in organizing and integrating relevant visual-spatial features, while drawing prompts based on sociocultural research engage students in discourse with their STEM community. Prior research has not synthesized work across theoretical perspectives to investigate how drawing prompts engage students in particular learning processes that enhance learning outcomes. Furthermore, the lack of synthesis has resulted in a lack of recommendations for effective designs of drawing prompts. Consequently, students do not always benefit from drawing prompts (Ainsworth et al., 2016; De Bock, Verschaffel, Janssens, Van Dooren, & Claes, 2003; Leutner, Leopold, & Sumfleth, 2009).

In the following, I first discuss my review of the literature in Chapter 2. I propose a new theoretical framework that synthesizes learning processes across theoretical perspectives and identifies gaps in prior work. I then address these gaps in four studies, detailed in Chapters 3-6, which investigated the effects of implementing drawing prompts across the theoretical perspectives. Particularly, I focused on drawing prompts for novice undergraduate students who are learning foundational STEM content in introductory-level courses. Little work has focused on how to help these students draw to learn STEM content, even though they are preparing to pursue careers as STEM professionals (de Vere et al., 2011; Quillin & Thomas, 2015; Uesaka & Manalo, 2012). Exploring the effects of drawing prompts can provide insight into what conditions drawing prompts are effective and potential mechanisms underlying how drawing prompts facilitate learning of visual-spatial content. Finally, in Chapter 7, I summarize my studies, provide suggestions for future work, and discuss the implications and contributions that emerge from this work.

# Chapter 2

## A Theoretical Framework of Six Learning Processes that Support Learning by Drawing[1]

Recent research has found growing empirical support for the effectiveness of drawing prompts (Ainsworth et al., 2011; Fiorella & Zhang, 2018). However, there is great variation in how prior work has implemented drawing prompts and, thus, uncertainty about how best to design them (Fiorella & Zhang, 2018; Quillin & Thomas, 2015; Tippett, 2016). To date, researchers have investigated a variety of drawing activities that address diverse learning goals such as translating scientific texts, increasing interest in STEM, enhancing observation skills during lab experiments, and representing complex phenomena in simulations (Ainsworth et al., 2011; Cooper, Stieff, & DeSutter, 2017; Fan, 2015; Quillin & Thomas, 2015). Such goals engage students in different processes and hence, shape the nature and design of drawing prompts.

In this dissertation, I focus on drawing prompts that help students learn visual-spatial STEM content through drawing on paper, in line with the goals of prior reviews (Leutner & Schmeck, 2014; Prain & Tytler, 2012; Van Meter & Garner, 2005). Even within this goal, a variety of drawing prompts have been implemented in different lines of research. Each line of research focuses on different instructional goals and broadly aligns with research within the cognitive and sociocultural theoretical perspectives (Nathan and Sawyer 2014). As illustrated in Figure 2.1, I consider this research to lie on a continuum that focuses on different learning goals, in which drawing activities may serve as a *cognitive tool* to help students think and make sense of visual-spatial concepts or a *sociocultural tool* to engage in disciplinary discourse. My review of cognitive research identified four learning processes that are fostered by drawing activities: (1) generative

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[1] [1] A published article of this work is available at: Wu, S. P. W., & Rau, M. A. (2019). How students learn content in science, technology, engineering, and mathematics (STEM) through drawing activities. *Educational Psychology Review, 31*(1), 87-120. https://doi.org/10.1007/s10648-019-09467-3.

learning, (2) self-regulation, (3) mental model integration, and (4) spatial cognition. My review of sociocultural research identified two additional processes: (5) mediated discourse and (6) disciplinary practices.

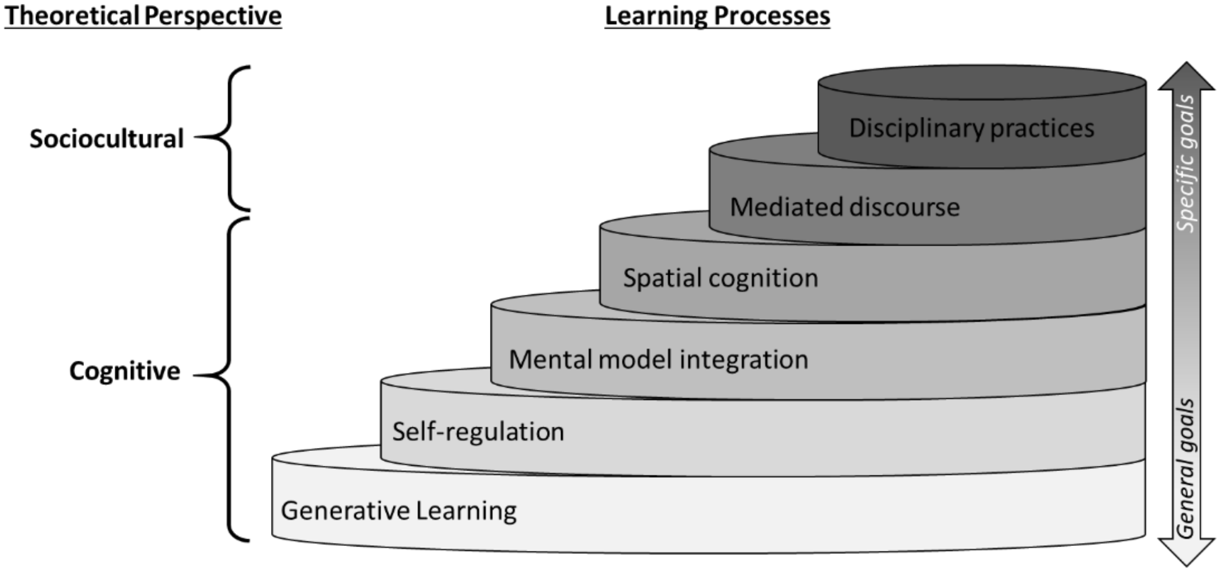

*Figure 1.* Six learning processes categorized by theoretical perspectives and organized in stacked circles that illustrate a focus from general to specific instructional goals.

I depict the six distinct learning processes as separate circles in Figure 2.1 to reflect the fact that separate lines of research have investigated each learning process. Consequently, each process corresponds to different ways in which drawing prompts engage students with content. Hence, I review prior research on each of the six learning processes in six separate subsections below to illuminate how research from different lines of research has facilitated students' learning of visual-spatial STEM content through drawing.

Further, I depict the learning processes in a "stacked" format in Figure 2.1 to illustrate that they build upon one another. In my review, I found that the processes with wider circles at the base address more general instructional goals, whereas the processes with narrower circles at the top address more specific instructional goals. The stacked circles illustrate that engaging in more specific learning processes also engages students in the more general processes below it. In each subsection below, I describe how the processes build on one another. Then, in the following section, I synthesize these relationships across the cognitive and sociocultural perspectives.

### Learning Processes from the Cognitive Perspective

Prior work from the cognitive perspective focuses on drawing as an instructional activity that can help students internally make sense of content (Chi & Wylie, 2014; Leutner & Schmeck, 2014; Van Meter & Firetto, 2013). Drawing activities engage students with to-be-learned content to help them actively reason about the content (*generative learning*), focus their interactions with the content on difficult concepts (*self-regulation*), integrate content with their prior knowledge (*mental model integration*), and reflect on content shown in their drawings (*spatial cognition*). Through these processes, drawing activities allow students to manage, organize, and explore the to-be-learned content (Fan, 2015; Jonassen, 2003).

***Generative learning.*** At a broad level, cognitive studies on drawing build on generative theories of learning (Osborne & Wittrock, 1983). This research shows that drawing activities enhance learning through increasing students' engagement with content (Fiorella & Mayer, 2015; Scheiter, Schubert, & Schüler, 2017). For instance, the ICAP framework suggests that learning increases from passive to active to constructive to interactive activities, as they increase students' engagement with the content (Wylie & Chi, 2014). The ICAP framework considers drawing activities to be *active* if students construct a drawing without engaging with content or their prior knowledge (e.g., copying an image). Drawing activities are more effective if they are *constructive*; that is, if students use drawing to build knowledge by integrating their prior knowledge with externally presented information. In support of this framework, experiments show that students who constructively generate their own drawings outperform those who actively trace or copy images (Gagnier, Atit, Ormand, & Shipley, 2016; Mason, Lowe, & Tornatora, 2013). Little work has compared the effects of drawing to other constructive activities that ask students to engage in physical movements (e.g., gesturing, manipulating objects) (Fiorella & Zhang, 2018). However, when compared to other constructive activities that ask students to integrate prior knowledge (e.g., summarizing text, interpreting illustrations), drawing activities typically yield enhanced or comparable learning outcomes (Fiorella & Mayer, 2015; Leopold & Leutner, 2012), although one study has found drawing was less effective than summarizing scientific texts (Leutner et al., 2009).

Thus far, most generative learning research focuses on how drawing activities help students learn from scientific texts, based on the Generative Theory of Drawing Construction (GTDC), proposed by Van Meter and Garner (2005). The GTDC builds on the dual-coding theory in multimedia learning that describes how students integrate visual and verbal information into their mental models (Mayer, 2014; Schnotz, 2014). Hence, studies based on the GTDC investigate how students translate verbal scientific texts into visual drawings via three stages. First, students select relevant information from the text to include in the drawing. Second, they organize this information spatially. Finally, they integrate multiple pieces of information into a coherent picture. For instance, to understand a text about the structure of the human heart, students identify which features of the heart to draw, organize the chambers of the heart in relation to one another, and integrate the information to show the connected chambers of the heart. Numerous studies based on the GTDC have found that drawing can help students learn visual-spatial information that is verbally presented in scientific texts (Leutner & Schmeck, 2014; Van Meter & Garner, 2005). In addition, this research shows that drawing activities can increase the accuracy and quality of drawings that students construct during the activities or enhance performance on pre-post drawing tests (Schmeck, Mayer, Opfermann, Pfeiffer, & Leutner, 2014; Schmidgall, Eitel, & Scheiter, 2018). Students with higher quality drawings tend to show enhanced performance on other learning outcome tests (Leutner & Schmeck, 2014; Van Meter & Garner, 2005).

Because drawing as a constructive activity increases mental effort, another outcome of generative learning is enhanced understand of complex concepts. Prior work has shown that higher-order assessments of complex knowledge are more sensitive to students' learning gains than assessments of simple knowledge (Gadgil, Nokes-Malach, & Chi, 2012; Leutner & Schmeck, 2014; Van Meter, Aleksic, Schwartz, & Garner, 2006). Additionally, a few studies have shown that drawing enhances long-term retention, even when accounting for the increased instructional time required for students to construct their own drawings (Mason et al., 2013; Wu & Rau, 2018).

In sum, research on generative learning suggests that drawing activities enhance learning if they increase students' cognitive engagement with content. Because generative learning focuses on general mechanisms of how drawing activities can more deeply engage students with content, each of the following processes also builds upon this goal.

***Self-regulation.*** Recent cognitive research focuses on self-regulation and metacognitive processes that describe how students use drawing to regulate their engagement with content (Hellenbrand, 2018; Schleinschok, Eitel, & Scheiter, 2017; Van Meter & Firetto, 2013). Broadly, research on these processes considers students' judgments of learning and behaviors that affect how they subsequently engage with content (Lajoie, 2008; Schraw, Crippen, & Hartley, 2006). Hence, this research does not primarily focus on students' learning of the content, but puts a stronger emphasis on how students *navigate* the content by drawing.

Prior research suggests that drawing activities enhance self-regulation processes by helping students self-assess and reflect on how well they understand the content (Schleinschok et al., 2017; Van Meter & Firetto, 2013). As a result, drawing may allow students to regulate how they engage with content more effectively and efficiently. Studies have shown that drawing activities help students externalize and self-assess their understanding, which in turn directs their attention to learning the content (Nyachwaya et al., 2011; Schmidgall et al., 2018; Van Meter, 2001). For example, a recent eye-tracking study showed that drawing activities help students direct their eye gaze to the conceptually-relevant parts of the content presented in text and transition more frequently between the relevant content and their drawing, when compared to activities that provide images or ask students to summarize (Hellenbrand, 2018).

In line with this work, a revised version of the GTDC, the Cognitive Theory of Drawing Construction (CTDC; Van Meter & Firetto, 2013), accounts for self-regulation by building on the frameworks for self-regulated learning (Winne & Hadwin, 1998) and integrated text and picture comprehension (Schnotz, 2002, 2005, 2014). The CTDC additionally considers students' learning goals in three stages. First, students set a goal based on the drawing task. Second, they translate the verbal text to visual information by selecting, organizing, and integrating text as described in the GTDC above. Finally, they monitor progress towards their learning goals by using visual information from the drawing to assess their understanding of the verbal information and revise the drawing as needed. This iterative process engages self-regulation processes in which students *plan* what content to draw, *monitor* changes to their understanding of the content, and *evaluate* their drawings to reflect these changes, as described in self-regulated learning model (Winne & Hadwin, 1998).

This research suggests that drawing prompts can help students self-assess what they do not yet know and then focus on content they do not understand. For instance, a study found that drawing activities helped undergraduate students determine what part of a text they needed to study in depth and that this monitoring predicted posttest performance more so than cognitive load

(Schleinschok et al., 2017). Further, recent research suggests that drawing activities may help students engage with content *efficiently* (Wu & Rau, 2018; Zhang & Linn, 2011). Thus, drawing activities may reduce instructional time with content if they help students self-assess, direct attention to the content they least understand, and adjust how they interact with content.

In sum, self-regulation research suggests that drawing activities may help students learn by focusing on the content that they least understand and self-regulate their engagement with content. According to the CTDC and recent research, self-regulation processes may build on generative learning processes by increasing students' engagement with content, particularly the content that they least understand. The CTDC is the first attempt to synthesize across the two processes and specify how self-regulation may subsume generative learning. Furthermore, the focus of self-regulation on self-assessment and reflection may help students engage with their mental models and drawings, as discussed in the process below.

***Mental model integration.*** Another related line of cognitive research, conceptual change, focuses on mental model integration, which describes how drawing can help students integrate new knowledge into their mental models (Gan, 2007; Vosniadou, 1994). These studies consider mental models as coherent structures that include both descriptive propositions of conceptually-relevant features and depictive structural relations between propositions (Chi, 2008; Schnotz, 2014; Vosniadou, 1994). Considering whether students' mental models are coherent is important because students can often generate correct statements (e.g., "the Earth is round"), even though they have incorrect mental models, or misconceptions (e.g., Earth as a flat disk). Misconceptions become apparent when students are prompted to draw their mental models (Harle & Towns, 2013; Vosniadou & Brewer, 1992). Studies have shown that students' initial drawings are often inaccurate, incomplete, or structurally incoherent, even if students are able to correctly answer multiple-choice questions about the same topic (Harle & Towns, 2013; Nyachwaya et al., 2011). Interview studies in which students draw and discuss their drawings have shown gaps and inaccuracies in their mental models because students often learn content by memorizing declarative statements or algorithms, which results in gaps and inaccuracies in their mental models (Cooper, Corley, & Underwood, 2013; Nyachwaya, Warfa, Roehrig, & Schneider, 2014; Papaphotis & Tsaparlis, 2008).

This line of research focuses on addressing gaps in students' mental models by integrating new content into them via generative learning and self-regulation processes. First, mental model integration seems to build on *generative learning processes* (Jonassen, Strobel, & Gottdenker, 2005). When students draw, they activate their mental models by selecting relevant features and organizing them in an external, coherent structure (Scheiter, Schleinschok, & Ainsworth, 2017). The external structure helps students encode and integrate new content to their prior mental models (Kirsh, 2010; Valanides, Efthymiou, & Angeli, 2013). As a result, students may expand and revise their mental models (Duit & Treagust, 2008; Vosniadou, 1994). Prior research shows that drawing prompts can help students develop more sophisticated mental models that align with content and incorporate their prior knowledge (Leopold & Leutner, 2012; Wang & Barrow, 2011). Such effects may not be immediately visible but may be measured on delayed posttests (Scheiter, Schubert, et al., 2017; Wu & Rau, 2018).

Second, conceptual change research also suggests that, to successfully integrate new concepts into mental models, students engage in effortful *self-regulation processes* to self-assess and change their mental models (Vosniadou, 2003). When students activate their mental models, they assess whether their mental models align with the content (Vosniadou & Brewer, 1992). If mental models do not align, students use one of two processes to integrate new content into their mental models (Chi, 2008; Vosniadou, 1994). First, *enrichment processes* allow students to add new information to *incomplete* mental models (Vosniadou, 1994). To do so, students need to identify gaps in their mental models and then add missing features to fill these gaps. Second, *transformation processes* allow students to change their mental models if they *conflict* with new content. In this case, students may have a mental model that does not meet scientific standards but holds true by a robust set of internal rules (e.g., young children may conceptualize the round earth as a flat disk to maintain their perception that the world is flat) (Vosniadou & Brewer, 1992). Studies show that prompting students to compare their mental models to content can help them identify and resolve conflicting mental models (Valanides et al., 2013; Vosniadou, 1994).

In sum, research on mental model integration suggests that drawing activities can help students activate their mental models and integrate new content into them. Mental model integration seems to build on generative learning and self-regulation processes to help students engage with their mental models. In addition, mental model integration focuses students on their drawings as an external assessment and learning tool, which is emphasized in the following process.

***Spatial cognition.*** Another line of cognitive research focuses on *spatial cognition*, which examines how students learn concepts through constructing and interpreting visual-spatial cues in their drawings (Bobek & Tversky, 2014; Cheng & Gilbert, 2009). This work considers drawing as a visual language in which visual-spatial cues depicted in drawings convey meaning and guide students' thinking (Kavakli & Gero, 2001; Tversky, 2011). In contrast to other cognitive research that focuses on engagement with content or mental models, research on spatial cognition considers how students engage with *drawings* both as a process and a product from which they interpret, transform, and relate visual features (Suwa, Tversky, Gero, & Purcell, 2001; Tversky, 2011).

Prior research on spatial cognition suggests that drawing activities help students make sense of concepts via bottom-up and top-down visual-spatial processes (Schwartz & Heiser, 2006; Tversky, 2011). Generally, when students are provided with visual representations, they use *bottom-up* processes when intuitive, salient cues (e.g., arrows, colors) help them identify relevant visual-spatial features (Chi & VanLehn, 2012; Tversky, 2011). For example, even if students are unfamiliar with a protein model with purple and green sections, they can identify that the two sections likely indicate different categories. Similarly, bottom-up processes are involved when students draw visual features and use cues, such as proximity, direction, and magnitude, to make inferences about the relation between the depicted features (Suwa et al., 2001; Tsang, Blair, Bofferding, & Schwartz, 2015; Tversky, 2011). Students use *top-down* processes when their prior knowledge about concepts helps them identify relevant visual-spatial features (Suwa et al., 2001; Tversky, 2011). Similarly, when students draw, they use top-down processes when they use their prior knowledge to generate visual-spatial features (Bobek & Tversky, 2014; Suwa et al., 2001). For instance, they may use their knowledge about spatial conventions (e.g., enclosed lines as boundaries, up is more) and disciplinary conventions (e.g., red indicates hot and blue indicates cold) to identify hot and cold boundaries in a map of the weather conditions. Further, students use top-down processes to map relationships from other content to those in their drawing (e.g., planets rotate around the sun → electrons rotate around the nucleus) (Gentner & Markman, 1997).

This line of research considers how students make sense of conceptually-relevant visual cues, or in particular, *structural relations* that describe how cues relate to one another (Gobert & Clement, 1999; Scheiter, Schleinschok, et al., 2017; Van Meter et al., 2006). When depicting structural relations in their drawings, students have to externalize their mental models and self-assess their understanding of the STEM content (Hegarty, 2004; Nyachwaya et al., 2011). While verbal descriptions allow students to vaguely describe relationships (e.g., “electrons surround the nucleus”), drawing requires them to explicitly depict structural relations (e.g., they can show electrons as clustered in ‘petals’ outside the nucleus or in rings circling the nucleus) (Anning, 1999; Vosniadou & Brewer, 1992). Further, drawing can amplify mental models by helping students “fill in” details that may be ambiguous in the mind (Fish & Scrivener, 2007). Hence, both the process and product of drawing activities can help students make sense of how concepts relate to visual cues and identify new structural relations between visual cues (Gobert & Clement, 1999; Scheiter, Schleinschok, et al., 2017; Van Meter et al., 2006).

Drawing activities have been shown to enhance learning outcomes with respect to four types of structural relations: visual, spatial, causal, and temporal. Visual relations typically depict the shape or aesthetic of features (e.g., non-symmetrical and rounded edges of the human heart). Spatial relations describe the relative orientation and distance among features (e.g., electrons are located outside of the nucleus). Causal relations show how features affect one another (e.g., the piston of a bike pump pushes air into a chamber). Temporal relations show changes in features over time (e.g., magma turns into lava). Drawing activities have been shown to help students learn about structural relations in a variety of STEM content, including the human heart, molecular chemical reactions, phases of the moon, and a virus on the immune system (Ainsworth et al., 2016; Leutner & Schmeck, 2014; Parnafes, Aderet-German, & Ward, 2012; Zhang & Linn, 2011). However, prior work has not systematically compared the effects of drawing prompts that target different structural relations. Spatial cognition research has primarily focused on how drawing activities help students learn visual and spatial relations. For example, a study prompted students to draw, mentally visualize, or copy visual representations of spatial relations among geological layers (Gagnier et al., 2016). Students who drew outperformed the other students because drawing helped them organize spatial relations among geological layers. By contrast, generative learning has primarily focused on causal and temporal relations in scientific texts, which organize concepts by time and sequence. This work shows that drawing activities are less or equally effective as higher-order text-based strategies (e.g., self-explanation, summarization) (Fiorella & Mayer, 2015; Gobert, 2005; Ploetzner & Fillisch, 2017).

In sum, research on spatial cognition suggests that drawing activities can help students learn content when students identify relevant structural relations in drawings via top-down and bottom-up processes. In these processes, spatial cognition engages students' mental models and builds upon their prior experience with visual representations, which suggests that this process relies on the other cognitive processes described above. These cognitive processes then seem to help students engage in sociocultural processes in which they participate in disciplinary discourse through constructing and interpreting drawings with their STEM community.

## Learning Processes from the Sociocultural Perspective

Prior research from the sociocultural perspective focuses on drawing as an activity that mediates students' meaning making of content when they participate in the discourse of the given STEM discipline. Generally, this perspective considers drawing as a tool to communicate with others in the environment (*mediated discourse*) and to develop ways of thinking appropriate to the discipline (*disciplinary practice*). Such interactions with drawings mediate students' learning of relevant disciplinary discourse and facilitate students' enculturation into STEM communities. Note that sociocultural perspectives do not strictly distinguish processes and outcomes. Rather, they consider the ability to engage in the learning process as a learning outcome. For instance, mediated discourse describes students' participation in discourse as the process and the ability to participate in discourse as a desired learning outcome.

Sociocultural research typically considers a multitude of learning goals which shape how students learn content through drawing. Prain and Tytler's (2012) Representational Construction Affordances (RCA) framework accounts for the variation in this research. The RCA framework defines three sociocultural factors that productively constrain how drawing activities mediate students' discourse and meaning making of content. First, *semiotic tools* constrain how students draw content via physical tools (e.g., paper and pencil), resources (e.g., peers), and conventions (e.g., O symbol for oxygen). These constraints encourage specific ways of drawing to represent the content and help students learn how to draw in accordance with specific disciplinary discourses. Second, *epistemic practices* constrain how students engage in STEM disciplinary practices such as knowledge building, inquiry, and problem solving. These constraints align with how STEM professionals draw content in their work (e.g., draw possible shapes of an antibody to identify how it binds to a virus). Engaging in such authentic practices constrains students' drawing of content in a way that reflects the processes of each disciplinary practice. Third, *epistemological processes* constrain knowledge building through the practice of constructing drawings for specific purposes. These constraints ensure that students depict specific aspects of STEM content that are appropriate for their STEM environment. In choosing and using specific types of representations, students learn how to draw in ways that address specific disciplinary goals and challenges. Taken together, the RCA describes how these interrelated productive constraints reflect the knowledge and practices in specific STEM disciplines such that students learn to draw content in accordance with the goals and paradigms of each discipline.

My literature review identified the RCA framework as the first to describe how students learn by drawing from a sociocultural perspective. Hence, I used this framework to organize prior sociocultural research on drawing activities, which focus on mediated discourse or disciplinary practices. *Mediated discourse* processes primarily account for research on semiotic tools. This research involves younger students in pre-kindergarten and primary school and focuses on how students draw to *communicate about content*. *Disciplinary practices* processes primarily account for research on epistemic practices. This research includes students from middle school to undergraduates and focuses on how students use drawing as a *tool to solve disciplinary problems*. Although there are similarities between these two lines of research in terms of the epistemological processes they consider, I find it useful to distinguish them because they have focused on two distinct sets of learning processes and learning outcomes, as discussed below.

***Mediated discourse.*** Sociocultural research on mediated discourse investigates drawing as an activity that mediates how students learn to engage in disciplinary discourse. Particularly, drawing activities help students reflect on how their drawings communicate visual-spatial content in their specific physical and social learning environment (Nathan, Eilam, & Kim, 2007; White & Pea, 2011). From this perspective, students' drawings are considered public, contextual, and developmental reflections of the social goals and context (Brooks, 2009; Roth & McGinn, 1998). Over time, engaging in drawing activities helps students communicate content in drawings and engage in the disciplinary discourse of their STEM community.

Research on mediated discourse describes a learning process through which students depict content in drawings that increasingly conform to the visual language used in specific STEM disciplines (Brooks, 2009; Enyedy, 2005; Prain & Tytler, 2012). Students make sense of disciplinary conventions and tools for each visual language through an iterative process. When students first draw to represent content, they often construct drawings with creative and non-conventional features that reflect their naïve and internally consistent misunderstandings (diSessa & Sherin, 2000; Stieff, Hegarty, & Deslongchamps, 2011). Then, by reflecting on and negotiating their drawings with others, students refine drawings to conform to scientific conventions that are appropriate for the context, goals, and members of the community (Greeno & Hall, 1997; Nathan et al., 2007). Over time, this process helps students develop proficiency in using disciplinary conventions to explore and communicate about new content. For example, Lehrer and Schauble (2003) found that a class of primary school students who regularly engaged in drawing activities were able to investigate and communicate about a novel dataset using drawings that align with disciplinary conventions. By contrast, students in another class who did not draw regularly focused on surface features of the same dataset without using drawing conventions.

As the main learning outcome, this line of research aims to help students develop sophisticated drawing practices that align with the historical development of disciplinary discourse in the STEM community (Johri et al., 2013; Latour, 1986; Nersessian, 2008). STEM communities adopt disciplinary conventions that help them communicate effectively with others in the given discipline (Greeno & Hall, 1997). Hence, drawings are effective tools for students' participation in discourse when they are clear, parsimonious, and explanatory representations of the content they depict (Greeno & Hall, 1997; Nathan et al., 2007). As students draw to participate in discourse, they learn drawing practices over time that help them make epistemological choices on what representations to draw as appropriate communication tools in the given discipline and context (Berland & Crucet, 2015; diSessa, 2004).

In sum, research on mediated discourse suggests that drawing activities can help students adopt and use disciplinary drawing conventions by participating in discourse within their community. Because of this focus on drawings, mediated discourse processes seem to build upon spatial cognition processes, while focusing on conventions used in specific disciplines. If mediated discourse builds on spatial cognition processes, then this research also builds on the other cognitive processes discussed above. Furthermore, because mediated discourse focuses on how students use drawing as a communication tool to participate in their STEM community, it can help students participate in the work of STEM professionals, as discussed in the following process.

***Disciplinary practices.*** Sociocultural research on disciplinary practices investigates drawing as a means to engage students with STEM professionals' epistemic ways of thinking in STEM disciplines. STEM professionals often draw to address specific disciplinary goals or problems, such as observing patterns, constructing representations of content, making predictions, communicating ideas with others, transforming representations, and synthesizing content (Cheng & Gilbert, 2009; Fan, 2015; National Research Council, 2012; Quillin & Thomas, 2015). As part of such practices, professionals draw to explore and reason with the relevant content (Arcavi, 2003; Latour, 1990), which then help them contribute ideas to the STEM community (Arcavi, 2003; Frankel, 2005). Hence, STEM instructors ask students to participate in similar disciplinary practices, in which students learn to use drawing as a tool to engage with content and enculturate into these practices (Cheng & Gilbert, 2009; Evagorou, Erduran, & Mäntylä, 2015).

This line of research considers how drawing can engage students in disciplinary practices (as learning processes) that characterizes students' ability to engage with content as professionals do (as learning outcomes). My review has identified two primary ways that students engage in disciplinary practices: scientific modeling and design practices. Scientific modeling practices are prevalent in the mathematics and science disciplines, while design practices are common in the engineering and technology disciplines (de Vere, Melles, & Kapoor, 2011; de Vries, 2006; Goldschmidt, 2014; Snyder, 2013).

*Scientific modeling* involves constructing representations to simplify, abstract, and examine content, which in turn helps students explain, predict, or solve authentic scientific problems in the real world (National Research Council, 2012; Schwarz et al., 2009). Drawing prompts are commonly used to help students model scientific concepts (Ainsworth et al., 2011; Cooper et al., 2017). Students may draw to make observations, reason about content, evaluate models, and synthesize information (Backhouse, Fitzpatrick, Hutchinson, Thandi, & Keenan, 2017; Evagorou et al., 2015; Fan, 2015; Quillin & Thomas, 2015). Prior research suggests that students engage with drawing activities in four stages: construction, use, evaluation, and revision (Quillin & Thomas, 2015; Schwarz et al., 2009). These stages emphasize the fact that students do not only focus on constructing drawings, but also use, evaluate, and revise them in order to solve scientific problems. One study showed that prompting students to construct predictive, observational, or reflection drawings at different points of an intervention helped students engage in these specific scientific modeling practices to learn content (Cooper et al., 2017).

*Design practices* also involve constructing and refining representations to solve a disciplinary problem. However, drawing activities for design practices invert the process typically involved in scientific modeling (de Vries, 2006). Instead of shifting from external objects to internal representations (representing objects/events in the real world → external representation → internal representation) as in scientific modeling, drawing activities for design practices involve shifting from internal representations to external objects (internal representation → external representation → objects/events in the real world). When designing to solve a disciplinary problem, students first use their internal cognitive, cultural, and social resources to construct drawings of their design ideas (Anning, 1999; Goldschmidt, 2003; Prain & Tytler, 2012). Then, students combine their creative ideas with external constraints related to STEM content such as available resources, structural limitations of the materials used, and physical constraints of the real world (de Vries, 2006; Purcell & Gero, 1998). Through this process, students can refine their ideas because drawings provide information on which constraints are not met or how the design can be improved (de Vries, 2006; Goldschmidt, 2003). For instance, when undergraduate engineering students attempt to design a desk accessory with a wide pencil cup and post-it holder, a drawing can help them determine if both features fit within the allotted specifications.

Both scientific modeling and design practices consider the development of students' professional drawing practices as an important learning outcome. Specifically, one aspect of this development is students' ability to transform content between real-world objects and internal representations. Drawings constructed by STEM professionals typically do not resemble the objects or phenomena they depict but are representations of content that scale, rotate, or highlight specific features (Latour, 1990; Palmer, 1978). For instance, biologists often enlarge the size of a cell and simplify specific components in drawings (e.g., a single line to represent the double layer of lipids that make up the cell wall). These representational transformations allow professionals to abstract, mathematize, and manipulate content in an intuitive, external form (Latour, 1990; Roth & Bowen, 1994). Thus, students must learn to draw a representative, abstract model that conveys conceptually relevant features. Novice students often construct initial drawings that resemble the referent and only show concrete features of phenomena (Brooks, 2009; Kozma & Russell, 2005). Qualitative analyses of students' drawings show a progression from concrete, object-bound drawings to abstract drawings that represent the referent (Brooks, 2009; Kozma & Russell, 2005; Lehrer & Schauble, 2003, 2015; Schwarz et al., 2009). Students' later drawings often include less detail and fewer features because students actively make choices about what to include and when, as appropriate for the given problem and context (Berland & Crucet, 2015).

Another important aspect in the development of students' professional drawing skills is engagement in revision. STEM professionals engage in iterative cycles of generating and revising drawings as they relate their drawing to the real world, using their expertise in drawing to rapidly transform content for further exploration (Kothiyal, Murthy, & Chandrasekharan, 2016; McCracken & Newstetter, 2001; Verstijnen, van Leeuwen, Goldschmidt, Hamel, & Hennessey, 1998). Case studies of STEM professionals show that they first use drawings to simplify problems into a qualitative model, which they then iteratively evaluate and revise through additional drawings (Kavakli & Gero, 2002; Kothiyal et al., 2016; Ullman, Wood, & Craig, 1990). Further, analyses of professionals' design processes show that designers first search for ideas through constructing rapid, manual drawings and then formalize ideas by interpreting their own drawings (Fish & Scrivener, 2007; Suwa et al., 2001). Each drawing helps designers "see" new structural relations and determine how to refine their designs in order to solve their design problem (Purcell & Gero, 1998). Prior work shows dramatic differences between professionals and novice students in their ability to rapidly transform and revise content for further exploration (de Vere et al., 2011; Jee et al., 2014; Kavakli & Gero, 2002), yet little work has examined how students develop such drawing skills (Johri, Olds, & O'Connor, 2014; Prain & Tytler, 2012).

In sum, research on disciplinary practices suggests that drawing activities can help students engage in specific disciplinary practices used by STEM professionals. Disciplinary practices encourage students to use their drawings as tools to transform content and solve disciplinary problems. In order to engage with content, disciplinary practices seem to rely on mediated discourse. Particularly, the ability to transform content in drawings and to rapidly revise drawings requires the use of disciplinary conventions and other semiotic tools within a discipline. However, although the RCA framework has suggested how the processes overlap, the processes have been investigated in different lines of research. Developmental studies typically focus on mediated discourse to investigate how younger students in pre-kindergarten and primary school represent and discuss content in their drawings (Brooks, 2009; Prain & Tytler, 2012). In contrast, research on disciplinary practices has primarily investigated how STEM professionals in the workplace use drawing as a tool to transform content and how students from middle schoolers to undergraduates often do not use drawing to learn content (de Vere et al., 2011; Ullman et al., 1990).

Furthermore, disciplinary practices processes seem to build on the cognitive processes. For instance, in scientific modeling, students must activate and self-assess their prior knowledge (as described in mental model integration and self-regulation) to revise, evaluate, and (re)construct a coherent model of the content (Cooper et al., 2013; Leenaars, Van Joolingen, & Bollen, 2013; Wilkerson-Jerde, Gravel, & Macrander, 2015). Moreover, disciplinary practices require students and professionals to "see" structural relations in their models (as described in spatial cognition). Hence, disciplinary practices may build on all of the cognitive and sociocultural processes above.

## Summary of Learning Processes

The review of prior research from the cognitive and sociocultural perspectives identified six distinct learning processes that can help students learn STEM content. They each engage students with content in a particular way, such as integrating content with mental models, interpreting content depicted in drawings, and discussing content through drawing. The separate lines of research on each learning process target increasingly specific aspects of the drawing task in order to help students engage with and learn the relevant STEM content. This work yields specific learning outcomes that align with each process, as summarized in Table 2.1.

My review also suggests that the six processes build upon one another, such that students engage in multiple learning processes when they engage in more specific processes. As shown in Figure 2.1, processes may "stack" on top of one another such that specific processes rely upon the more general processes below it. Each successive "stacked" process engages students in drawing activities that help students achieve more specific learning goals.

Table 2.1
*A summary of six learning processes underlying how drawing helps students learn STEM content with the theoretical perspectives and learning outcomes that they align with.*

| **Theoretical perspective** | **Learning Process** | **Learning Outcomes** |
|---|---|---|
| Cognitive | Generative learning<br>(*Construct knowledge by translating content*) | • Increase quality of drawings<br>• Enhance performance on higher-order and long-term assessments |
| Cognitive | Self-regulation<br>(*Self-assess understanding of content to direct one's interaction with content*) | • Identify what students least understand and self-regulate engagement with content<br>• Increase efficiency with learning materials |
| Cognitive | Mental model integration<br>(*Activate mental models and revise them to integrate content*) | • Identify incomplete or inaccurate mental models<br>• Develop more sophisticated mental models that integrate content |
| Cognitive | Spatial cognition<br>(*Identify structural relations using top-down / bottom-up processes*) | • Learn visual, spatial, causal, temporal, and/or functional structural relations in visual-spatial STEM content |
| Sociocultural | Mediated discourse<br>(*Use disciplinary tools to represent and discuss content*) | • Use disciplinary conventions to engage with new content<br>• Develop drawing practices to participate in disciplinary discourse |
| Sociocultural | Disciplinary practices<br>(*Transform content to solve disciplinary problems*) | • Transform content between real-world objects and internal representations<br>• Develop adaptive drawing skills |

The "stacked" relationship between the learning processes for drawing activities aligns with the broader landscape of cognitive and sociocultural research on learning, which examines different units of analysis. Nathan and Alibali (2010) describe cognitive research as focusing on elemental and fine-grained units of analysis that examine individual elements of a complex system, while sociocultural research focuses on systematic and coarser-grained units of analysis that examine complex systems. Coarse-grained analyses at the systemic level *supervene* on the elemental components such that any change at the systemic level implies a change at the elemental level (Sawyer, 2005). The six learning processes I identified from prior research on drawing activities suggest that the processes from sociocultural perspectives supervene those from the cognitive perspectives. Further, within each perspective, certain processes with specific learning goals supervene others with more general goals. The alignment between the drawing literature and broader literature on learning processes suggests that prior research has investigated drawing activities with different units of analysis that correspond to the level at which they operate. These processes seem to be interrelated and built upon one another, as shown in Figure 2.1, rather than separate processes that may each require different types of drawing prompts.

If the learning processes are interrelated, then drawing prompts may be designed to engage students in multiple processes at the same time. For instance, a drawing prompt on atomic structure that targets a disciplinary problem (disciplinary practices) may help students engage with a text that describes atoms (generative learning), map structural relations about the location of electrons (spatial cognition), and discuss what conventions can depict electrons with peers (mediated discourse). To support these processes, instructors may provide drawing prompts that indicate what content to draw, ask students to reflect on the targeted content during and after instruction, and facilitate peer interaction or instructor feedback on the drawings (Cooper et al., 2017; Wagner, Schnotz, Stieff, & Mayer, 2017). These multiple types of support can facilitate different aspects of students' interaction with content (e.g., how they process the content in relation to mental models and relate the content shown in drawings) while supporting the mutual goal of engaging students with the targeted content. Thus, drawing prompts designed for multiple learning processes may serve complementary roles that help students learn visual-spatial STEM content.

## How This Dissertation Addresses Gaps in Prior Research

Although some prior research on drawing has begun to combine multiple learning processes (Prain & Tytler, 2012; Van Meter & Firetto, 2013), my review is the first to identify how drawing prompts can facilitate multiple learning processes across the cognitive and sociocultural perspectives to help students learn STEM content. To the best of my knowledge, no empirical work has tested whether drawing prompts are effective when designed to target multiple learning processes across theoretical perspectives. Specifically, prior research has not investigated whether drawing prompts that are designed to support learning processes from the cognitive perspectives also support learning processes from the sociocultural perspective and vice versa. Such research would provide evidence towards whether learning processes from the sociocultural perspective supervene those from the cognitive perspective, as proposed in Figure 2.1.

In this dissertation, I address this gap in prior work by conducting four studies with novice undergraduate STEM students to investigate the effects of drawing prompts that target multiple learning processes. Because prior work has not determined whether learning processes across theoretical perspectives build upon one another, the primary goal of each study is to investigate whether drawing prompts that target multiple learning processes are effective in helping students learn STEM content. Furthermore, to understand how drawing prompts may engage multiple learning processes across the perspectives, a secondary goal of each study is to examine the ways in which students used drawings to make sense of visual-spatial concepts (in accordance with the focus of the cognitive perspective) and engage in disciplinary discourse (in accordance with the additional focus of the sociocultural perspective).

In Study 1, I first investigated the effects of drawing prompts that focus on mental model integration from the cognitive perspective. In line with other cognitive studies, I conducted Study 1 as an experiment in the laboratory. In this experiment, I investigated the effects of drawing prompts for novice undergraduate students as they learned introductory-level chemistry concepts. Based on my review of prior research in Chapter 2, I designed drawing prompts for mental model integration that also build on generative learning and self-regulation processes. Specifically, the prompts asked students to activate and revise their mental models through iterative engagement with the content and their drawings. By investigating the effects of these prompts, when compared to providing additional instructional time with content, Study 1 addresses a theoretical question of whether drawing prompts that focused on generative learning, self-regulation, and mental model integration are effective in helping students learn visual-spatial STEM content. In addition, Study 1 compares the effects of providing drawing prompts at different times to address a practical question about when to prompt students to draw as they engage with content so that students can effectively engage in multiple learning processes.

Based on the results from Study 1, I then conducted Studies 2-4 in three STEM courses to investigate the effects of drawing prompts for multiple learning processes in authentic contexts, in alignment with prior sociocultural research (Johri et al., 2014; Prain & Tytler, 2012). These prompts combined prior research across the two theoretical perspectives in order to investigate whether learning processes across perspectives build upon each other.

In Study 2, I investigated the effects of a drawing prompt that targeted disciplinary practices in a chemistry course, when compared to a modeling prompt (another disciplinary practice) and to no prompts (business-as-usual). I designed drawing and modeling prompts to help students visualize concepts and solve problems in STEM, as suggested by research on disciplinary practices. In addition, both prompts can engage students in cognitive processes. For instance, they both require physical movements with visuals, which can increase cognitive engagement, in line with research on generative learning. By comparing the effects of drawing to another disciplinary practice, Study 2 addresses a theoretical question of whether and how drawing prompts that target disciplinary practices may particularly promote other learning processes from the cognitive or sociocultural perspective. Furthermore, Study 2 addresses a practical question of how drawing prompts engage students with content in an authentic classroom setting when instructors and peers may also facilitate drawing and other disciplinary practices.

Based on the results of Study 2, I then conducted Study 3 to extend my research on drawing prompts to an electrical engineering course. This study investigated the effects of drawing prompts for disciplinary practices throughout a semester-long course. The drawing prompts incorporated recommendations from Studies 1 and 2 as well as prior work across the cognitive and sociocultural perspectives. Study 3 addresses a theoretical question of whether drawing prompts that combine multiple recommendations across theoretical perspectives are effective throughout a semester-long course. Furthermore, it addresses a practical question of how students engaged with and perceived the role of drawing as they learned content over a semester.

Based on the results of Study 3, I then conducted Study 4 to investigate two types of drawing prompts for disciplinary practices. Specifically, I designed two drawing prompts that focused on qualitative reasoning (interpreting drawings) or quantitative reasoning (translating drawings to formulas). Qualitative drawing prompts focused on helping students use their drawings to reason about concepts and focused on features valued by their STEM community, as suggested by research on mediated discourse and disciplinary practices from the sociocultural perspective. Quantitative drawing prompts focused on identifying relevant features in their drawings and using these to determine the appropriate mathematical operations, as suggested by research on spatial cognition from the cognitive perspective and disciplinary practices from the sociocultural perspective. By comparing these two types of prompts, Study 4 addresses a theoretical question on whether drawing prompts that focused on different learning processes within perspectives or across perspectives are more effective. Further, it addresses a practical question of how drawing prompts can provide more specific guidance to help students use their drawings to learn content.

Taken together, these studies provide insight into the conditions in which drawing prompts are most effective. Particularly, they show whether drawing prompts can facilitate multiple learning processes across theoretical perspectives and how they engage students with content through drawing. Because prior research has not investigated the effects of drawing prompts that target multiple learning processes across theoretical perspectives, this work provides theoretical insights into how the learning processes may build upon one another in complementary ways that enhance learning outcomes. Furthermore, the findings yield new research directions and practical recommendations on how to combine prior research on learning processes from the cognitive and sociocultural perspectives such that drawing prompts optimally engage students in multiple learning processes in STEM courses.

Below, I present Studies 1-4 in Chapters 3-6. In each chapter, I first provide a background on the learning goals of each context to describe how I designed drawing prompts that align the learning goals with the specific learning processes described in this chapter. Then, I discuss how each study investigated different types of drawing prompts that can help novice undergraduate students learn visual-spatial STEM content.

# Chapter 3

## Study 1: Investigating Drawing Prompts for Multiple Cognitive Processes[2]

Study 1 investigated whether drawing prompts that focus on generative learning, self-regulation, and mental model integration processes enhance novice undergraduate students' learning of chemistry content. As suggested by my framework in Chapter 2, these three cognitive processes build upon one another such that mental model integration processes also engage generative learning and self-regulation processes. Therefore, I designed drawing prompts to help students integrate content with their prior knowledge (via mental model integration), which should also increase cognitive engagement (via generative learning) and focus their interactions with content (via self-regulation).

In this study, I compared the effects of implementing drawing prompts in an educational technology that helps undergraduate students learn about atoms using visual representations. Hence, in the following, I first provide background on how students learn with visual representations, particularly in an educational technology. Then, I discuss how prompting students to draw their own representations can enhance their learning on three learning outcomes: First, I assessed increased engagement with content using immediate and long-term posttests (generative learning). Second, I investigated the effect of self-regulation by examining instructional efficiency (self-regulation). Third, I examined changes in students' drawings over time to determine how students align their mental models with new content (mental model integration). Results on these outcomes provide insight into whether drawing prompts that target mental model integration are effective in helping students learn visual-spatial STEM content via multiple cognitive processes.

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[2] A published article of this work is available at: Wu, S. P. W., & Rau, M. A. (2018). Effectiveness and efficiency of adding drawing prompts to an interactive educational technology when learning with visual representations. *Learning and Instruction*, 55, 93–104. https://doi.org/10.1016/j.learninstruc.2017.09.010.

## Background

As discussed in Chapter 1, instruction in the STEM domains often provides pre-generated visual representations to students, such as those shown in the bottom of Table 1.1 to help students explore chemistry concepts. Hence, students' learning of domain knowledge critically depends on their ability to make sense of visual representations (Gilbert, 2005; Mathewson, 1999). However, prior research shows that students struggle to learn with visual representations because they must identify conceptually relevant features and make connections among multiple visual representations (Ainsworth, 2006b; Rau, 2017).

To help students overcome these difficulties, instructors may provide visual representations to students using *educational technologies*, which have been shown to be particularly effective at helping students learn STEM content (Rau, Bowman, & Moore, 2017; Stieff, 2011). Educational technologies can provide instructional support via prompts and error-specific feedback that help students attend to specific features in visual representations (Rau, 2016; Rau, Aleven, Rummel, & Pardos, 2014). The support in technologies typically prompt for verbal sense-making processes because prior research has shown that students benefit from *verbally explaining* how multiple representations depict concepts (Koedinger, Corbett, & Perfetti, 2012; Wylie & Chi, 2014).

However, verbal explanation may not help students learn visual-spatial content that depicts relations between features (e.g., spatial arrangement of electrons in an atom), which can be difficult to explain verbally (Tversky, 2011). Further, as discussed in Chapter 2, students may not realize gaps in their knowledge until they are prompted to draw their mental models (Harle & Towns, 2013; Vosniadou & Brewer, 1992). For example, when drawing their own representation of an atom, students may externalize their own mental model about the spatial arrangement between electrons in an atom, compare how they organize features in their drawing in relation to the content, and identify a gap in their mental model about the shape of electron clouds. Such support may help students identify what they least understand in their drawing, which then also facilitates self-regulation processes (how they interact with instruction) and generative learning processes (engaging more deeply with content) (Zhang & Linn, 2011).

To help students engage in mental model integration, drawing prompts can guide students' interactions with visual representations by asking them to (1) generate and (2) revise drawings of representations. First, prompts to *generate* drawings can help students identify and organize the relevant features of representations, as suggested by prior research on generative learning (Bobek & Tversky, 2014; Van Meter & Firetto, 2013). Generate prompts have been shown to enhance learning outcomes (Van Meter & Garner, 2005; Zhang & Linn, 2011), particularly if students generate high quality drawings that align with content (Scheiter, Schleinschok, et al., 2017; Schmeck et al., 2014). Second, prompts to *revise* drawings may help students remedy inaccuracies within their mental models and integrate new content (Vosniadou, 1994). In this process, students may potentially engage with their own (flawed) drawings and revise them towards high quality drawings, as suggested by prior research on mental model integration and self-regulation. Some recent work has shown that revise prompts enhance students' learning of STEM content, particularly if prompts are provided repeatedly (Prain & Tytler, 2012; Valanides et al., 2013). However, prior research has not tested the effects of prompts to generate and revise drawings for learning with visual representations.

Further, prior work has not systematically investigated how to implement *repeated* drawing prompts to generate and revise in educational technologies. One methodological concern is that additional drawing prompts increase instructional time, leading to differences in time-on-task for drawing and non-drawing conditions (e.g., Leutner & Schmeck, 2014; Van Meter, 2001). Prior research controlled for time-on-task by comparing drawing prompts to prompts for other time-intensive activities (e.g., summarizing text) (Leopold & Leutner, 2012). However, no prior work has *replaced* instructional activities with drawing prompts to control for time-on-task and assessed the efficiency of prompts.

To address these gaps, I implemented drawing prompts in an educational technology that ask undergraduates to draw their own visual representations on paper. Specifically, I compare a condition (a) that did not provide drawing prompts to two experimental conditions with (b) two drawing prompts before and after instruction and (c) four drawing prompts throughout instruction. In line with research on generative learning, the drawing prompts ask students to generate and revise drawings may promote cognitive engagement with content. To determine whether these drawing prompts enhance learning outcomes, I investigate **RQ1.1:** Are drawing prompts *effective*? I assess effectiveness as learning gains on an immediate and delayed posttest on chemistry content.

The implementation of repeated drawing prompts may also help students self-assess and focus on the concepts they least understand, as suggested by prior research on self-regulation (Zhang & Linn, 2011). Hence, the prompts may increase students' learning efficiency with content. That is, they learn more content in less time with drawing prompts. Specifically, I investigate **RQ1.2:** Are drawing prompts *efficient*? I assess efficiency as learning gains on an immediate and delayed chemistry posttest while accounting for time-on-task.

I account for time-on-task in two ways. First, at the level of condition, I control for time-on-task by adjusting the number of instructional activities such that all conditions spent about the same amount of time on average across all activities (i.e., instructional activities and drawing). Students who received drawing prompts completed fewer instructional activities to account for the time they would spend drawing. Second, at the individual level, I account for time-on-task with instructional efficiency measures proposed by van Gog and Paas (2008) because students worked on activities at their own pace. I consider drawing prompts to be *effective* if they enhance students' learning gains and *efficient* if they enhance students' learning gains in less instructional time.

Finally, to examine how prompts engaged students with drawings and content, I assessed *drawing quality* in terms of alignment with the visual representations in Table 1.1. Changes in students' drawings over time can indicate how students align their mental models with new content, in line with research on mental model integration. However, because I cannot compare drawings across time for each condition (e.g., the control condition did not receive drawing prompts during instruction), I conducted a qualitative analysis of drawings to investigate **RQ1.3**: Do prompts to generate and revise drawings affect the quality of students' drawings?

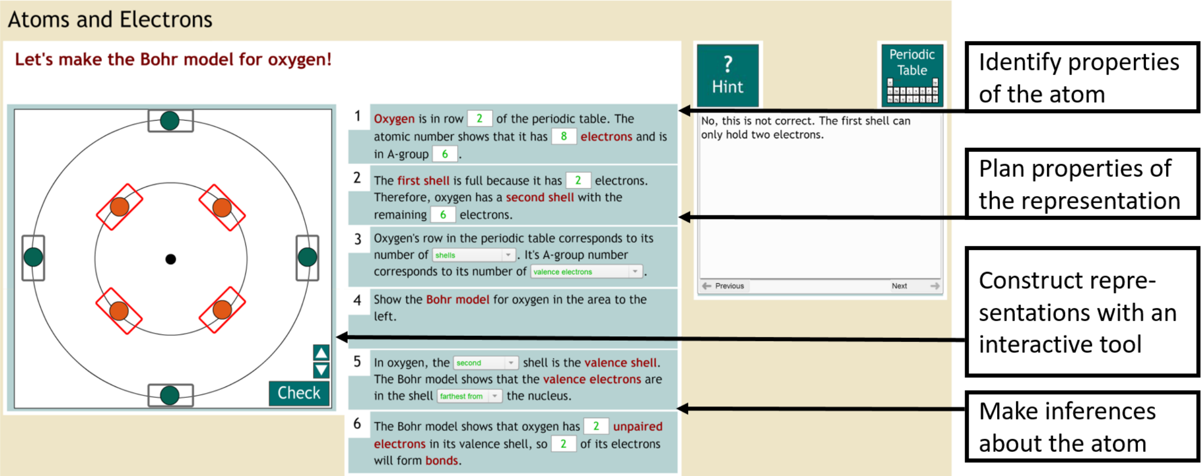
## Method

I address these research questions in a laboratory experiment with 72 undergraduate students from an educational psychology course. Most of these students have taken at least one introductory-level college chemistry course (68.1%) and some have taken an intermediate-level course (22.2%).

I randomly assigned students to three conditions. Students in the *no-prompt* condition (*n* = 24) received no drawing prompts. Students in the *before-after* condition (*n* = 23) received prompts only before and after they worked on instructional problems. Students in the *throughout* condition (*n* = 25) received prompts before and after as well as throughout instructional problems. All students sat at a computer with paper and pens available throughout the experiment.

**Educational technology: Chem Tutor**. Students worked on interactive instructional problems using Chem Tutor, an educational technology for undergraduate chemistry (Rau, 2015;

Rau, Michaelis, & Fay, 2015). For all interactions, Chem Tutor provided error-specific feedback and on-demand hints (Rau et al., 2015). All students first received an introduction to the four visual representations of atoms shown in Table 1.1: Lewis structures, Bohr models, energy diagrams, and orbital diagrams. Then, they worked on two problem sets in which they used representations to learn about atomic structure.



Atoms and Electrons

Let's make the Bohr model for oxygen!

1 Oxygen is in row 2 of the periodic table. The atomic number shows that it has 8 electrons and is in A-group 6.

2 The first shell is full because it has 2 electrons. Therefore, oxygen has a second shell with the remaining 6 electrons.

3 Oxygen's row in the periodic table corresponds to its number of shells. It's A-group number corresponds to its number of valence electrons.

4 Show the Bohr model for oxygen in the area to the left.

5 In oxygen, the second shell is the valence shell. The Bohr model shows that the valence electrons are in the shell farthest from the nucleus.

6 The Bohr model shows that oxygen has 2 unpaired electrons in its valence shell, so 2 of its electrons will form bonds.

No, this is not correct. The first shell can only hold two electrons.

*Figure 3.1*. Example instructional problem about the Bohr model of oxygen in Chem Tutor.

An example Chem Tutor problem is shown in Figure 3.1. First, students identify properties of the atom and plan the representation by completing fill-in-the-blank explanations. Next, they use an interactive tool to construct the representation by placing electrons and energy levels on the atom. Finally, students make inferences about the atom based on the representation.

**Drawing prompts.** Students in the prompted conditions (before-after, throughout) received *generate* and *revise* prompts between Chem Tutor problems. Generate prompts asked: “Draw what comes to mind when you think about the concept: ‘atom’” because “this exercise will help you understand how you see the atom.” Revise prompts asked: “Review your drawing, labels, and captions. Revise them as needed.” After each prompt, students were asked to rate the accuracy of their drawings to ensure students generated or revised their drawings.

**Time-on-Task.** To control for time-on-task between conditions, I calculated expected time-on-task for Chem Tutor problems and drawing prompts using data from pilot studies and prior studies with Chem Tutor. I used the expected time-on-task to adjust the number of Chem Tutor problems provided per condition. The no-prompt condition received 92 Chem Tutor problems, which took students an average of 31 minutes, as conducted in a prior study (Rau & Wu, 2015). To accommodate two drawing prompts, the before-after condition received 48 Chem Tutor problems (corresponding about 26 minutes). To accommodate four drawing prompts, the throughout condition received 44 Chem Tutor problems (corresponding to about 22 minutes).

**Assessments.** I assessed learning gains using three isomorphic *chemistry tests* about atoms (9 items), counterbalanced across test times (pre-test, post-test, and delayed-test). For RQ1.1, I computed *effectiveness* as a proportion of total possible correct answers. For RQ1.2, I computed *efficiency* using normalized test scores for performance ($z_{P_{\text{test}}}$) and time-on-task for invested mental effort ($z_{E_{\text{learning}}}$), as discussed by van Gog and Paas (2008):

$$\text{Instructional efficiency} = \frac{z_{P_{\text{test}}} - z_{E_{\text{learning}}}}{\sqrt{2}}$$

I computed total *time-on-task* as the sum of time spent on all Chem Tutor and drawing activities for each student.

Because spatial skills affect students' learning with visual representations (Stieff, 2007), I also assessed *spatial skills* using the Vandenberg & Kuse mental rotation test (Peters et al., 1995).

Finally, I assessed the quality of student drawings using video recordings to identify when student generated and revised drawings. Because the type of representations students chose to draw affected which features they drew, I coded drawings using a two-step process (see Appendix A for the full coding scheme). First, I categorized the *type of drawing* by counting features in the drawing that aligned with the representations presented in Chem Tutor (see Table 1.1). Drawings that did not align with any of the four representations were categorized as "Other." Second, I graded the *accuracy of drawing* by rating features shown in the drawing on a scale of 0 (inaccurate) to 4 (accurate). Two independent coders graded 11% of the drawings using the two-step process; grading was highly reliable (*ICC*s(2, 2) = .98 and .91, Shrout & Fleiss, 1979).

Table 3.1
*Overview of the procedure by session and condition. Drawing prompts are shown in bold red text and tests are shown in grey backgrounds for emphasis.*

| | | Condition | | |
|---|---|---|---|---|
| | | Throughout | Before-after | No-prompt |
| Session 1 | Pre-test | X | X | X |
| | Spatial test | X | X | X |
| | **Generate prompt** | **X** | **X** | |
| | Introduction | X | X | X |
| | **Revise Prompt 1** | **X** | | |
| | Problem Set | X | X | X |
| | **Revise Prompt 2** | **X** | | |
| | Problem Set | X | X | X |
| | **Revise Prompt Final** | **X** | **X** | |
| | Post-test | X | X | X |
| | | *One week delay* | | |
| Session 2 | **Generate prompt** | **X** | **X** | |
| | Delayed-test | X | X | X |

**Procedure.** Table 3.1 provides an overview of the procedure for each condition. The experiment involved two sessions, one week apart. Session 1 took approximately 90 minutes. Students first took the pre-test and spatial skills test. Then, they worked with the version of Chem Tutor that corresponded to their condition. Finally, students completed the post-test. In Session 2, all students were prompted to generate a drawing and then completed the delayed-test.

## Results

Table 3.2
*Means and standard deviations (in parentheses) of students' test scores by condition.*

| | | Chemistry test | | |
|---|---|---|---|---|
| Condition | Spatial test | Pre-test | Post-test | Delayed-Test |
| Throughout | .64 (.27) | .26 (.17) | .44 (.15) | .54 (.16) |
| Before-after | .70 (.16) | .39 (.16) | .51 (.16) | .51 (.15) |
| No-prompt | .70 (.18) | .33 (.20) | .49 (.22) | .51 (.21) |

Table 3.2 shows means and standard deviations of test scores by condition.

***Prior Checks***. First, I checked for differences between conditions at the pre-test and spatial test. A one-way ANOVA with condition as the between-subjects factor and pre-test scores as the dependent measure showed a marginal main effect of condition on pre-test, $F(2, 69) = 2.926$, $p = .060$. The same one-way ANOVA with spatial test scores as the dependent measure showed no significant differences between conditions on the spatial test, $F(2, 69) = .747$, $p = .478$. However, spatial test scores were significantly correlated with post-test ($r = .29$, $p = .01$), and delayed-test ($r = .42$, $p < .001$) as well as marginally correlated with pre-test ($r = .23$, $p = .05$). Therefore, I included pre-test and spatial test scores as covariates in analyses below.

Next, I checked whether time-on-task differed between conditions, using a one-way ANOVA with condition as the between-subjects factor and time-on-task as the dependent measure. There was a significant main effect of condition, $F(2, 69) = 6.566$, $p = .002$. The no-prompt condition spent significantly more time-on-task than the before-after condition, $t(46) = 3.585$, *p(adj)* = .002, $d = 1.009$. This difference in time-on-task resulted from drawing conditions taking less time for drawing prompts than expected based on pilot tests. Moreover, the before-after condition took significantly less time on the final drawing prompt than the throughout condition, $t(45) = 2.488$, $p = .019$, $d = .720$. Table 3.3 shows means and standard deviations for total time-on-task and duration of drawing activities by condition.

Table 3.3

*Mean and standard deviations (in parentheses) of duration for time-on-task (in minutes) and prompts (in seconds).*

| Condition | Time-on-task (minutes) | Prompt duration (seconds) Generate | Revise 1 | Revise 2 | Revise Final |
|---|---|---|---|---|---|
| Throughout | 53.32 (7.66) | 85.54 (45.24) | 19.80 (34.45) | 18.64 (27.13) | 28.32 (31.77) |
| Before-after | 49.95 (7.42) | 70.88 (29.66) | - | - | 12.17 (9.99) |
| No-prompt | 58.65 (9.67) | - | - | - | - |

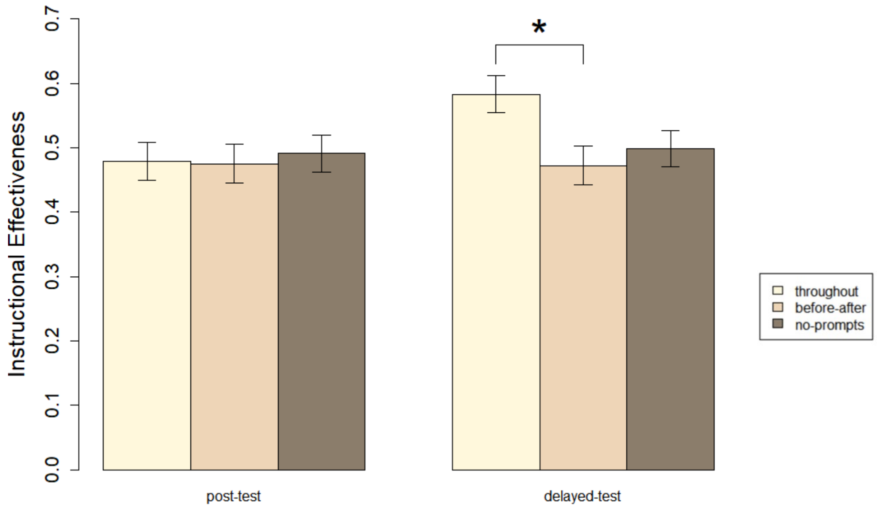


*Figure 3.3*. Estimated marginal means for instructional effectiveness at post-test and delayed-test by condition. Error bars show standard errors. * = $p < .05$.

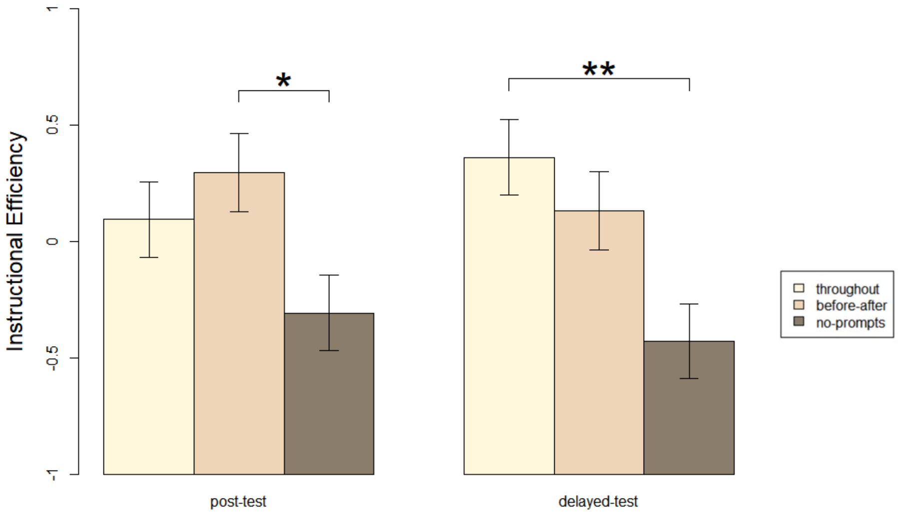


*Figure 3.4*. Estimated mean instructional efficiency at post-test and delayed-test by condition. Estimated means are shown on a standardized scale from -1 to 1. Error bars depict standard errors. * $p < .05$. ** $p < .01$.

***Effects of Drawing Prompts.*** To test **RQ1.1** (*instructional effectiveness* of drawing prompts), I used a repeated-measures ANCOVA with test-time (post-test, delayed-test) as the repeated within-subjects factor, condition as the between-subjects factor, pre-test and spatial test scores as covariates, and test scores as dependent measures. I found a significant interaction of test-time with condition, $F(2, 67) = 4.201$, $p = .019$, $\eta_p^2 = .111$. Post-hoc analyses showed no differences between conditions at post-test, *F*(2, 67) = .078, *p* = .925. However, there was a significant difference at the delayed-test, *F*(2, 67) = 3.881, *p* = .025, $\eta_p^2$ = .104. The throughout condition outperformed the before-after condition, *t*(47) = 2.643, *p(adj)* = .031, *d* = .782, but not the no-prompt condition, *t*(46) = 2.100, *p(adj)* = .121. As summarized in Figure 3.3, drawing prompts *throughout instruction* were more effective than drawing prompts before and after instruction, but only at the delayed-test.

To test **RQ1.2** (*instructional efficiency* of drawing prompts), I used the same ANCOVA model with efficiency scores as dependent measures. I found a significant main effect of condition, *F*(2, 67) = 5.051, *p* = .009, $\eta_p^2$ = .131. The throughout condition, *t*(48) = 3.465, *p(adj)* = .003, *d* = .992, and the before-after condition, *t*(46) = 2.599, *p(adj)* = .035, *d* = .757, were significantly more efficient than the no-prompt condition. Mean instructional efficiency scores for the throughout (*M* = .228, *SD* = .769) and before-after conditions (*M* = .213, *SD* = .769) were significantly higher than for the no-prompt condition (*M* = -.367, *SD* = .755). Further, there was a significant interaction of test-time with condition, *F*(2, 69) = 4.324, *p* = .017, $\eta_p^2$ = .114. Post-hoc analyses showed medium-sized differences between conditions at the post-test, *F*(2, 67) = 3.556, *p* = .034, $\eta_p^2$ = .096, and large-sized differences at the delayed-test, *F*(2, 67) = 6.372, *p* = .003, $\eta_p^2$ = .160. The before-after condition was significantly more efficient than the no-prompt condition at the post-test, *t*(46) = 2.599, *p(adj)* = .035, *d* = .757, but not at the delayed-test, *t*(46) = 2.401, *p(adj)* = .058. The throughout condition was significantly more efficient than the no-prompt condition at the delayed-test, *t*(48) = 3.465, *p(adj)* = .003, *d* = .992, but not at the post-test, *t*(48) = 1.758, *p(adj)* = .250. There were no significant differences between mean instructional efficiency scores for the throughout and before-after conditions, $t < 1$. There were also no significant interactions between these conditions at the post-test, *t*(47) = .852, *p(adj)* = 1.000, or at the delayed-test, *t*(47) = .983, *p(adj)* = .989. As summarized in Figure 3.4, drawing prompts enhanced instructional efficiency if prompts were provided throughout instruction (especially at the delayed-test) and before and after instruction (especially at the post-test).

***Changes in Drawing Quality.*** To explore **RQ1.3** (changes in drawing quality over time), I compared the accuracy of students' drawings between conditions. Because the number of drawings by type and condition was low (*n* < 5), I qualitatively analyze the accuracy of drawings.

Table 3.4
*Mean drawing accuracy scores for each type of representation by time of prompt and condition. Drawing scores range from 0-4. Underlined text highlights the mean score for first drawing prompt for each condition, Test times (pre-test, post-test, delayed-test) are shown to facilitate analysis of change over time.*

| | **Type of Representation** | | | | | |
|---|---|---|---|---|---|---|
| | Lewis | Bohr | Energy | Orbital | Other | **Total** |
| **Session 1** | | | | | | |
| *Before Instruction (Pre-test)* | | | | | | |
| Throughout | 4 | 2.82 | - | - | 1.06 | **1.86** |
| Before-after | 3.33 | 2.36 | - | 1 | 1.17 | **1.83** |
| *During Instruction* | | | | | | |
| Throughout | 3.5 | 2.43 | 1.5 | 2.75 | - | **2.38** |
| *After Instruction (Post-test)* | | | | | | |
| Throughout | 4 | 3.4 | 1 | 3 | - | **3.10** |
| Before-after | 4 | 2.5 | - | 4 | 1 | **3.25** |
| **Session 2** *(Delayed-test)* | | | | | | |
| Throughout | 4 | 3.17 | - | 2.5 | 0.89 | **2.42** |
| Before-after | 4 | 2.3 | - | 2.5 | 1.4 | **2.08** |
| No-prompt | - | 2.58 | - | 3 | 0.7 | **1.83** |

Table 3.4 shows that mean accuracy scores differed by drawing type, time of drawing, and condition. Qualitative inspection of total means shows that students generated the least accurate drawings when they were first prompted to draw: The drawings of students in the no-prompt condition in session 2 achieved accuracy scores (*M* = 1.83) as low as the scores for the drawings of students in the throughout (*M* = 1.83) and before-after conditions (*M* = 1.86) in session 1 before instruction. For the two prompted conditions, drawing accuracy improved similarly during session 1: at the post-test after instruction, accuracy scores were similar (*M* = 3.10 for the throughout

condition and *M* = 3.25 for the before-after condition). In session 2, drawing accuracy was highest for the throughout condition (*M* = 2.42), lower for the before-after condition (*M* = 2.08), and lowest for the no-prompt condition (*M* = 1.83).

## Discussion

This study investigated the effects of repeated drawing prompts to generate and revise representations. Quantitative results show that repeated drawing prompts throughout instruction were more effective at the delayed test, compared to prompts provided before and after instruction (**RQ1.1**). Further, providing drawing prompts is more efficient than not providing prompts (**RQ1.2**). Qualitative analyses of drawing quality showed that providing prompts, particularly throughout instruction, seemed to increase the quality of students' drawings over time (**RQ1.3**).

One main finding is that the frequency of prompts affects instructional effectiveness: providing drawing prompts *throughout instruction*—particularly prompts to *revise* drawings—was more effective at a delayed posttest than providing prompts only before and after instruction. In fact, after one week without instruction, students prompted to draw throughout instruction achieved higher quality drawings and learning gains at the delayed posttest. The additional drawing prompts may help students engage in difficult learning processes that overshadow immediate performance (Schweppe & Rummer, 2016). Recall that the additional drawing prompts focus on *reviewing and revising* drawings, which may help students engage in processes such as self-regulation and mental model integration (Chi, 2008; Vosniadou, 1994). My findings suggest that, when students draw, repeated drawing prompts throughout instruction may be needed to help them benefit from drawing activities.

Results also showed that drawing prompts were not more effective than additional instructional time on problems with verbal explanation in enhancing content knowledge. In accordance with the goals of generative learning, both types of instruction may have increased cognitive engagement with concepts. However, I also found that drawing prompts improved drawing quality. This suggests that drawing prompts may change the nature of students' engagement with content to learn content *visually*, not verbally, even though both types of engagement may be similar in enhancing learning outcomes on a chemistry test.

Another main finding is that providing drawing prompts resulted in *efficient* learning: students who received drawing prompts scored higher after less instructional time than students who received more instructional problems. Specifically, drawing prompts enhanced instructional efficiency if prompts were provided throughout instruction (especially at the delayed-test) and before and after instruction (especially at the post-test). Drawing prompts may have helped students grasp more concepts in less time via self-regulation because drawing directed students' attention to concepts they least understand and directed their interaction with instruction to focus on these concepts (Bobek & Tversky, 2014).

In sum, the results suggest that drawing prompts designed to facilitate mental model integration can enhance multiple learning outcomes, particularly enhanced mental models (an outcome of mental model integration) and increased efficiency (an outcome of self-regulation). On a theoretical level, Study 1 suggests that drawing prompts can facilitate general learning processes by targeting a more specific learning process such as mental model integration. On a practical level, Study 1 suggests that students benefit from *repeated* drawing prompts. This finding extends prior work by showing when to provide drawing prompts as students engage with content.

**Limitations of Study 1.** I identified several limitations in Study 1 that I aim to address in the following studies. First, my experiment focused on a specific chemistry topic: atomic structure. While atomic structure is similar to many other STEM topics because it uses multiple representations that depict visual-spatial concepts, additional research should investigate whether the results generalize to other STEM topics. Second, my participants were undergraduate students not majoring in science. Their study motivation and interactions with drawing prompts may differ from students majoring in chemistry or other STEM domains. To address these limitations, Study 2 focuses on a different chemistry topic (molecular structure) for students enrolled in a chemistry course.

Third, the results suggest that additional drawing prompts were effective at enhancing understanding of content after a delay (an outcome of generative learning), but drawing prompts were not more effective than additional time with instruction. Prior research on generative learning has shown that higher-order assessments are more sensitive to the effects of drawing than tests of simple knowledge (Leutner & Schmeck, 2014; Van Meter & Garner, 2005). Because Study 1 did not use a higher-order assessment, the effectiveness of drawing prompts may be unmeasured. To address this limitation, Study 2 assesses students' learning on tests of retention and transfer to separate the effects of drawing prompts on learning of simple and complex knowledge.

Finally, because this study only focused on learning processes from the cognitive perspective (mental model integration, self-regulation, and generative learning), it is unclear whether the findings generalize to learning processes from the sociocultural perspective. To address this limitation, the following studies investigate the effects of drawing prompts that support sociocultural processes for undergraduate students in the context of STEM classrooms. Specifically, Study 2 compares the effects of drawing prompts for two types of disciplinary practices.

# Chapter 4

## Study 2: Comparing Two Prompts for Disciplinary Practices[3]

Study 2 contrasts the effects of drawing prompts to modeling prompts, which target another disciplinary practice promoted by STEM instructors. Prompts for undergraduate students often target disciplinary practices to help them solve problems in specific STEM disciplines as professionals do (Brint, Cantwell, & Hanneman, 2008; National Research Council, 2012). In my framework (see Figure 2.1), I depict disciplinary practices as the most specific learning process that also engages students in more general learning processes such as reflecting on their understanding of content (self-regulation), translating content to drawings (generative learning), and discussing their drawings with peers (mediated discourse). To engage students in these processes and help undergraduate students solve problems in a STEM classroom, I designed prompts that focus on drawing on paper or using physical models.

In this study, I compare drawing prompts or modeling prompts in an educational technology, to a business-as-usual chemistry lab course with no prompts. Below, I first discuss how these prompts address the learning goals of undergraduate chemistry students, including collaboration in a classroom context. Then, I examine the effects of the prompts on students' learning of chemistry knowledge on a retention and transfer test. The transfer test, a higher-order assessment, may be more sensitive to the effects of drawing prompts than the retention test of simple knowledge, as shown in prior research on generative learning (Leutner & Schmeck, 2014; Van Meter & Garner, 2005). In addition, I explore instructors' impressions of how students used their models and drawings to engage in disciplinary practices within the classroom context. Results

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[3] A published article of this work is available at: Wu, S. P. W., Corr, J., & Rau, M. A. (2019). How instructors frame students' interactions with educational technologies can enhance or reduce learning with multiple representations. *Computers & Education*, 128, 199-213. https://doi.org/10.1016/j.compedu.2018.09.012.

from this study will provide insight into whether drawing prompts promote learning processes from the cognitive and sociocultural perspectives. Further, it will show how drawing prompts in particular affect students' learning outcomes, when compared to modeling prompts which also engage students in physical and cognitive engagement with content (Fiorella & Zhang, 2018).

### Background

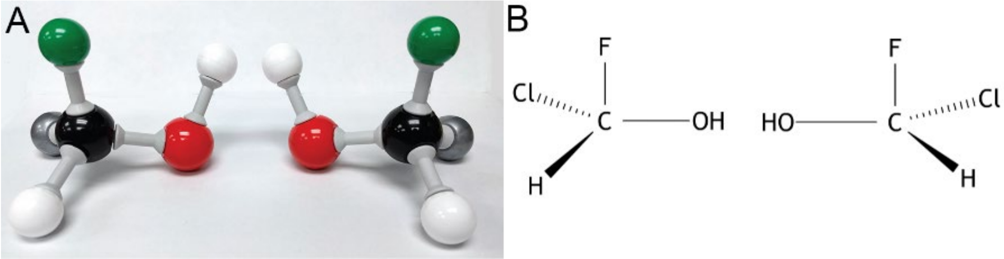


*Figure 4.1.* Physical 3D ball-and-stick model (A) and 2D wedge-dash structure (B). Each shows two isomers, molecules with the same atoms but different 3D spatial arrangement of the atoms.

Instructors play a crucial role in helping their students interact with content in STEM classrooms. Particularly, because visuals are prevalent in STEM domains, instructors often help students learn content by translating among multiple visual representations (Ainsworth, 2008; Kozma, 2003). For instance, to learn about molecular geometry, undergraduate chemistry students may translate the physical 3D models into 2D drawings, as shown in Figure 4.1. Yet, prior research shows that students often have difficulties with such translations, which can severely impede their learning in STEM domains (Ainsworth, 2008; Rau, 2017; Stull, Hegarty, Dixon, & Stieff, 2012). Translating requires students to map visual features of one representation to corresponding features in the other representation. To do so, students have to hold visual features in working memory and mentally rotate these features to align them (Hegarty & Waller, 2005). Because students with low spatial skills struggle with mental rotation tasks, translation activities are particularly difficult for these students (Hegarty & Waller, 2005; Stieff, 2007).

To help students overcome difficulties in translating among representations, instructors traditionally utilize *collaboration* because students can help each other map visual features and make sense of how representations show key concepts (van Dijk, Gijlers, & Weinberger, 2014). Furthermore, collaboration may particularly help students with low spatial skills receive support from peers to help them align and map features among multiple representations (Levine, Foley, Lourenco, Ehrlich, & Ratliff, 2016; Nichols, Hanan, & Ranasinghe, 2013).

Prior work on translation also focuses on *educational technologies* to help students translate among multiple representations (Rau, Aleven, & Rummel, 2015; Seufert, 2003). Technologies can provide immediate feedback on translation activities and prompt students to map specific visual features of representations (Rau, 2016; Rau et al., 2014). Akin to the support provided by instructors, technologies can adapt to students' needs by directing attention to aspects of representations that students least understand (VanLehn, 2011).

To help students collaboratively translate from the 3D models to 2D drawings shown in Figure 4.1, Rau, Bowman, and Moore (2017) developed and tested an educational technology that adaptively provided prompts to discuss representations, when students reached an impasse during translation activities. An experiment showed higher learning gains for students who received the technology than for students who worked on the same activities without technology. Observations of the students who received the technology in this experiment showed that instructors prompted students to engage in two practices. First, instructors prompted students to *construct and orient a 3D model* before translating to a virtual drawing within the educational technology, where they would receive feedback on their drawing. Second, instructors prompted students to use the 3D model to *generate an intermediary 2D drawing on paper* before generating the virtual drawing to receive feedback from the educational technology.

These two practices correspond to two disciplinary practices in STEM domains (National Research Council, 2012). STEM professionals often construct physical models and generate intermediary drawings on paper to engage with new content (via generative learning), formatively self-assess their own understanding (via self-regulation), and participate in disciplinary discourse (via mediated discourse) (Brew et al., 2012; Goldschmidt, 2003; Kavakli & Gero, 2001). However, it is unclear which practice is more effective for undergraduate students because prior research provides mixed views on whether these two practices enhance or hinder learning of content knowledge, as discussed in the following.

First, prior research suggests that focusing students' interactions on physical models can help them learn content knowledge (Pouw, van Gog, & Paas, 2014; Stull et al., 2012). The physical action of orienting models can help students learn how to rotate 3D models for projection onto the 2D plane (Pouw et al., 2014; Stull et al., 2012). Further, physically rotating models may alleviate difficulties in mental rotation for students with low spatial skills (Höffler, 2010; Pouw et al., 2014). However, some research suggests that focusing students' interactions on physical models could hinder learning because students do not know how to spatially align models (Barrett, Stull, Hsu, & Hegarty, 2014). Because students can freely rotate physical models, they may not orient the models to facilitate translation into 2D drawings, compared to students who watch an instructor or technology orient 3D models for them (Barrett & Hegarty, 2016; Springer, 2014).

Second, prior research shows that drawing can help students learn content knowledge (as discussed in Chapter 2), particularly from translation activities in chemistry (Cooper et al., 2017; Zhang & Linn, 2011). Drawing on paper may be more effective than drawing on the computer because students can physically rotate the paper to align with the physical model, easily share their drawings, and quickly make changes to their drawings (Leutner & Schmeck, 2014; White & Pea, 2011). Yet, research shows that drawing is cognitively demanding (Schwamborn, Thillmann, Opfermann, & Leutner, 2011). As a result, students, particularly those with low spatial skills, may focus on generating the drawing without mapping features across representations.

In sum, prior work has not determined whether focusing on drawing on paper or modeling will enhance or hinder learning outcomes. These two practices may help students better engage with the content as professionals do via disciplinary practices and learning processes from the cognitive and sociocultural perspective. However, the practices may also hinder students who do not yet have the skills to use models or drawings, especially students with low spatial skills. Because it is unclear how the prompts affect students' learning outcomes, I compare the effects of an educational technology with prompts that focus on physical models or on intermediate drawings on paper to a business-as-usual control condition that did not use technology or receive a prompt. Specifically, I investigate **RQ2.1**: Are prompts more effective than business-as-usual in enhancing content knowledge if they focus on physical models or on intermediary drawings on paper?

Further, because translating between representations is particularly difficult for students with low spatial skills (Hegarty & Waller, 2005; Stieff, 2007), I investigate the effect of spatial skills on learning outcomes in **RQ2.2**: Do students' spatial skills moderate the effects of modeling and paper prompts?

Finally, to explore how students engaged with the models and paper drawings, I conducted interviews with instructors to investigate **RQ2.3**: What are instructors' impressions of how modeling and paper prompts affected students' engagement with models and drawings?

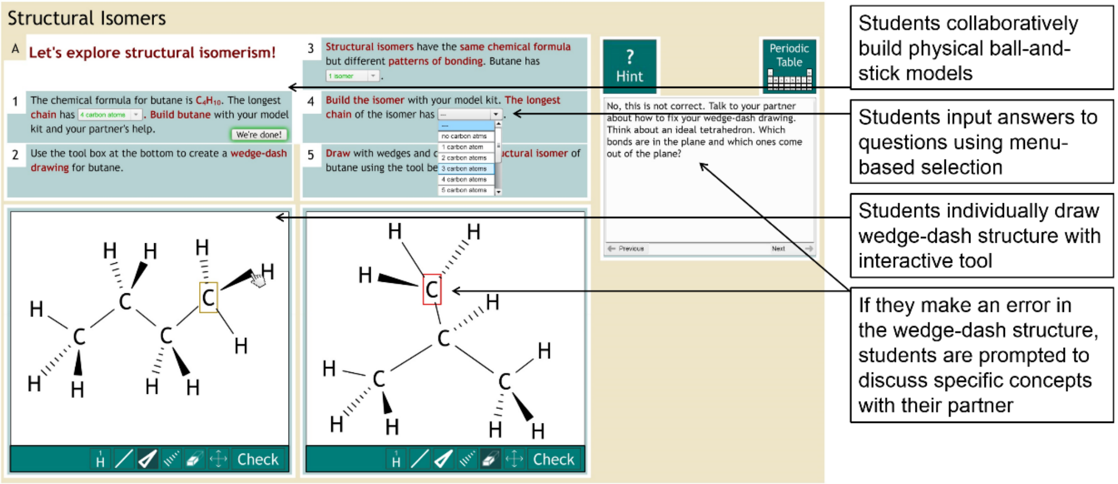
## Method

I address these research questions using a quasi-experiment with 565 students in an undergraduate chemistry course. The quasi-experiment took place during a 3-hour lab session that was led by teaching assistants (TAs). This lab session covered chemical isomers, molecules made of the same atoms that differ in the spatial arrangement of their atoms. Instruction on isomers crucially relies on connecting the representations shown in Figure 4.1. Differences in the atoms' spatial arrangements within molecules can have dramatic effects on the properties of chemical compounds (e.g., melting point, optical activity).

To learn about isomers, students collaboratively solved a sequence of chemistry problems. Each problem instructed students to construct a physical 3D ball-and-stick model of a specific isomer using a shared modeling kit. Then, the problem asked students to draw the 2D wedge-dash structure and complete conceptual questions about concepts related to the specific isomer.

**Experimental design.** Of the total 34 lab sections, I assigned 23 sections to a business-as-usual *control condition* (*n* = 383 students). Students in this condition drew wedge-dash structures and answered conceptual questions on a paper worksheet. At the end of the lab session, TAs collected the worksheets to provide written feedback in the following week's lab session.

The remaining 11 sections were assigned to two experimental conditions in which students drew wedge-dash structures in an educational technology: Chem Tutor. As introduced in Study 1, Chem Tutor is an educational technology for undergraduate chemistry that provides error-specific feedback and on-demand hints (Rau, 2015; Rau, Michaelis, et al., 2015). In this study, students used Chem Tutor to complete the identical sequence of chemistry problems (i.e., same questions, same molecules) that was provided in the paper worksheet of the control condition, as in the prior study (Rau et al., 2017). However, students drew the wedge-dash structure in an interactive tool and answered conceptual questions using drop-down menus (Figure 4.2). If students made an error, Chem Tutor provided immediate feedback by highlighting the incorrect part of the wedge-dash structure or conceptual question that was incorrect and asking students to discuss the related concept with their partners.



Structural Isomers

A Let's explore structural isomerism!

1 The chemical formula for butane is $C_4H_{10}$. The longest chain has 4 carbon atoms. Build butane with your model kit and your partner's help.

2 Use the tool box at the bottom to create a wedge-dash drawing for butane.

3 Structural isomers have the same chemical formula but different patterns of bonding. Butane has 1 isomer.

4 Build the isomer with your model kit. The longest chain of the isomer has --- .

5 Draw with wedges and c … uctural isomer of butane using the tool be …

No, this is not correct. Talk to your partner about how to fix your wedge-dash drawing. Think about an ideal tetrahedron. Which bonds are in the plane and which ones come out of the plane?

Students collaboratively build physical ball-and-stick models

Students input answers to questions using menu-based selection

Students individually draw wedge-dash structure with interactive tool

If they make an error in the wedge-dash structure, students are prompted to discuss specific concepts with their partner

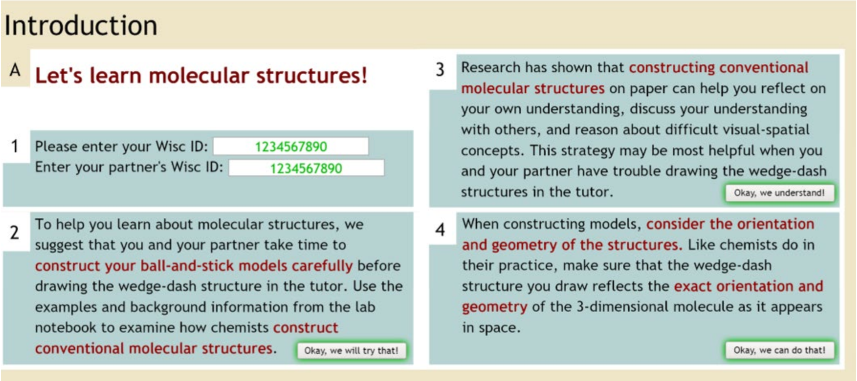
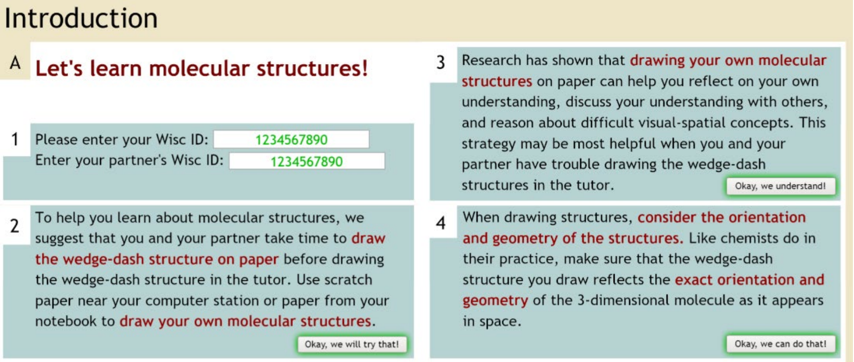
*Figure 4.2.* An example chemistry problem about structural isomers in Chem Tutor.

I assigned five lab sections to the *model condition* (*n* = 75 students) and six lab sections to the *draw condition* (*n* = 107 students). The difference between the model and the draw conditions regarded an introductory prompt on the first page of Chem Tutor and a spoken prompt provided at the beginning of the lab session, shown in Table 4.1. Students in the *model condition* received prompts to "carefully build and orient their physical ball-and-stick models" before constructing drawings in Chem Tutor. Students in the *draw condition* received prompts to "plan their wedge-dash structures on paper" before constructing them in Chem Tutor. The respective prompts stated that the practice of "constructing models" or "drawing on paper" benefits students because it "aligns with the work of professional chemists and is an essential part of their reasoning process." Both prompts aimed to help students engage with the content through disciplinary practices in which they map features across representations while collaborating with peers. Further, the drawing prompt aimed to help students self-assess as they "plan" on paper.

**Assessments.** I assessed students' learning of domain knowledge using a *pretest* and *posttest* on isomers, evaluated in the prior study (Rau et al., 2017). A *retention scale* of the test assessed students' ability to recall isomer concepts from the lab. A *transfer scale* assessed students' ability to apply this knowledge to predict the stability of molecules.

I assessed students' *spatial skills* using the Vandenberg & Kuse test for mental rotation ability (Peters et al., 1995), which was used in prior chemistry learning research (e.g., Stieff, 2007).

Table 4.1
*Prompts provided to students in the experimental conditions (model, draw). Underlined text in the oral prompts emphasizes differences between prompts.*

| Condition | Introduction | Prompt |
|---|---|---|
| Model | Oral | A beneficial strategy is to carefully build and orient your physical models before drawing on the computer. We know that working with physical models is different from drawing on the computer for your brain development, but we don't have the technology to provide feedback on your physical models yet. After you orient your model, draw it again on the tutor—a step that also helps your understanding—to get feedback. This strategy of constructing models aligns with the work of professional chemists and is an essential part of their reasoning processes. |
| | Introductory text in Chem Tutor | <br>Introduction<br>A Let's learn molecular structures!<br>1 Please enter your Wisc ID: 1234567890<br>Enter your partner's Wisc ID: 1234567890<br>2 To help you learn about molecular structures, we suggest that you and your partner take time to construct your ball-and-stick models carefully before drawing the wedge-dash structure in the tutor. Use the examples and background information from the lab notebook to examine how chemists construct conventional molecular structures. Okay, we will try that!<br>3 Research has shown that constructing conventional molecular structures on paper can help you reflect on your own understanding, discuss your understanding with others, and reason about difficult visual-spatial concepts. This strategy may be most helpful when you and your partner have trouble drawing the wedge-dash structures in the tutor. Okay, we understand!<br>4 When constructing models, consider the orientation and geometry of the structures. Like chemists do in their practice, make sure that the wedge-dash structure you draw reflects the exact orientation and geometry of the 3-dimensional molecule as it appears in space. Okay, we can do that! |
| Draw | Oral | A beneficial strategy is to plan your wedge-dash drawings on paper before drawing on the computer. We know that drawing on paper is different from drawing on the computer for your brain development, but we don't have the technology to provide feedback on paper drawings yet. After you plan on paper, draw it again on the tutor—a step that also helps your understanding—to get feedback. This strategy of drawing on paper aligns with the work of professional chemists and is an essential part of their reasoning processes. |
| | Introductory text in Chem Tutor | <br>Introduction<br>A Let's learn molecular structures!<br>1 Please enter your Wisc ID: 1234567890<br>Enter your partner's Wisc ID: 1234567890<br>2 To help you learn about molecular structures, we suggest that you and your partner take time to draw the wedge-dash structure on paper before drawing the wedge-dash structure in the tutor. Use scratch paper near your computer station or paper from your notebook to draw your own molecular structures. Okay, we will try that!<br>3 Research has shown that drawing your own molecular structures on paper can help you reflect on your own understanding, discuss your understanding with others, and reason about difficult visual-spatial concepts. This strategy may be most helpful when you and your partner have trouble drawing the wedge-dash structures in the tutor. Okay, we understand!<br>4 When drawing structures, consider the orientation and geometry of the structures. Like chemists do in their practice, make sure that the wedge-dash structure you draw reflects the exact orientation and geometry of the 3-dimensional molecule as it appears in space. Okay, we can do that! |

I assessed instructors' *impressions* via semi-structured interviews with four TAs: two who taught sections assigned to the draw condition (Daniel, Dylan) and two who taught sections assigned to the model condition (Michael, Macy).[4] Macy also taught a section assigned to the control condition. Each TA received $5 for participating in a 30-minute interview.

**Procedure.** Students enrolled in the undergraduate chemistry course attended a lecture in week 3 of the semester that covered molecular geometry and chemical isomerism. In week 4, they worked on activities in accordance with their typical lab schedule. First, as the required pre-lab exercise, they completed the pretest and spatial test online. Then, during their scheduled 3-hour lab session, they completed problems using Chem Tutor or worksheet that corresponds to their condition. Lastly, they completed the posttest online as the required post-lab exercise at the end of week 4. Two weeks after the lab, I conducted interviews with TAs.

## Results

Table 4.2
*Means and standard deviation (in parentheses) of test scores by condition. Scores are calculated as a proportion of total possible correct answer, on a scale from 0 to 1.*

| | Condition | | |
|---|---|---|---|
| | Control | Model | Draw |
| Spatial test | .881 (.140) | .875 (.132) | .857 (.166) |
| Reproduction scale | | | |
| Pretest | .527 (.190) | .515 (.170) | .541 (.186) |
| Posttest | .651 (.195) | .630 (.202) | .628 (.210) |
| Transfer scale | | | |
| Pretest | .540 (.403) | .654 (.397) | .727 (.369) |
| Posttest | .745 (.356) | .801 (.326) | .764 (.375) |

Table 4.2 shows the means and standard deviations of test scores by condition.

**Manipulations checks.** I first checked for prior differences between conditions. A multivariate analysis of variance (MANOVA) with condition as the independent factor and test

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[4] All TA names are pseudonyms, selected to match TA's assigned experimental condition (draw, model).

scores (reproduction pretest, transfer pretest, and spatial skills test) as dependent measures showed no significant differences between conditions on the reproduction pretest ($F < 1$) or on the spatial skills test, $F(1, 564) = 1.313$, $p = .270$. However, there was a significant difference on the transfer pretest, $F(1, 564) = 10.527$, $p < .001$. Post-hoc comparisons showed that students in the draw condition had significantly higher scores than students in the control condition ($p < .001$). To account for pretest differences, all following analyses used transfer pretest scores as a covariate.

**Differences in learning gains between conditions.** First, I investigated **RQ2.1** (whether modeling and paper prompts enhance content knowledge, compared to the control) and **RQ2.2** (whether spatial skills moderate the effects of the prompts). Because students taught by the same TA may have more similar knowledge than students taught by different TAs, I used a hierarchical linear model (HLM) with a random intercept for TAs to take into account nested sources of variance. The HLM included transfer pretest scores as a covariate to control for pretest differences prior to the intervention, condition as the independent factor to test research question 4.1, and spatial skills and an interaction effect of condition with spatial skills to investigate research question 4.2. On the reproduction posttest, there was no significant main effect of condition ($F < 1$) nor a significant interaction between condition and spatial skills ($F < 1$). On the transfer posttest, there was a significant main effect of condition on learning gains, $F(2, 547) = 5.445$, $p = .005$, such that the model condition outperformed the control condition, which outperformed the draw condition. This effect was qualified by a significant interaction between condition and spatial skills, $F(2, 547) = 5.383$, $p = .005$. To gain insights into the interaction effect, I split students into groups with low (0-33rd percentile on the spatial skills test), medium (34th-66th percentile), and high spatial skills (67th-100th percentile). Post-hoc comparisons showed that the effect of condition was marginally significant among students with low spatial skills, *F*(2, 544) = 2.654, *p* = .071, but not among students with medium or high spatial skills, *p*s > .10.

**TA impressions.** Next, I qualitatively investigated **RQ2.3** (instructors' impressions of students' engagement with models and drawings) using TA interviews on how students engaged with models and paper drawings during the lab session.

On engagement with models, TAs articulated that students, particularly those in the draw condition, "stopped building models" (Daniel) without "prodding" (Dylan), even though models were beneficial to their learning. One TA in the model condition, Michael, stated that students "can learn more deeply when they try to convert from [models]…to the computers." All of TAs discussed how Chem Tutor helped students address questions with models because the feedback from the technology addressed "simpler questions" (Macy) and freed time for TAs to "built the models with [students] and spend more time with them" (Dylan)

On engagement with drawings, TAs articulated that Chem Tutor helped students interact with drawings. They all suggested adding *more* prompts to draw on paper "before or after they do it on the computer" (Macy) to help with "muscle memory" for the test (Dylan) or for their own understanding because "they can easily draw the molecules" (Michael). Only Macy, upon reflection during her interview, stated that "all the isomer questions were more easily understood by the people who did the computer-based section," realizing that Chem Tutor with the modeling prompt may be more effective than prompting students to draw on paper.

## Discussion

This study investigated whether prompts for two disciplinary practices affected students' learning as they collaboratively translated from physical 3D models to 2D drawings in a chemistry course. Results show that prompting students to focus on physical models *enhanced* learning gains on a transfer test, whereas prompting students to focus on generating intermediary drawings on paper *reduced* learning gains, compared to a business-as-usual control condition that received no technology (**RQ2.1**). These effects were particularly pronounced for students with low spatial skills (**RQ2.2**). However, these results contradict the impressions of instructors, who preferred the practice of generating intermediary drawings on paper—the least effective practice (**RQ2.3**).

My results suggest that modeling prompts were more effective than paper prompts in enhancing knowledge transfer. Focusing students on physical models may have helped students, particularly those with low spatial skills, get support from their partner in spatially orienting models to map features onto 2D drawings. Recall that students shared a modeling kit and thus had to discuss and negotiate how to build models collaboratively. These students may have benefited from engaging in the sociocultural process of mediated discourse which help them learn to use models as communication and thinking tools. In contrast, observations of classroom activity for students who received paper prompts showed that they often drew intermediary drawings individually on their own paper, which reduced opportunities for mediated discourse. Further, observations showed that students often copied their drawing into the technology to get feedback. Cognitive research on generative learning suggests that copying drawings can result in lower learning gains than constructing drawings because copying engages students actively, but not constructively or interactively (Gagnier et al., 2016; Mason et al., 2013). Hence, the paper prompts may not have adequately supported students in cognitive and sociocultural processes that build on disciplinary practices.

Instructors may implicitly engage in cognitive and sociocultural processes to solve problems in their discipline, which explains why the TAs in this study recommended more paper prompts, in contrast to the finding that this practice was least effective. Instructors may fail to recognize which aspects of a task are most difficult for students because they have an expert blind spot (Nathan & Petrosino, 2003). They value drawing on paper because it is effective for them as STEM professionals. They may regularly use drawings to engage with new content (via generative learning) and participate in disciplinary discourse with colleagues (via mediated discourse) (Brew et al., 2012; Goldschmidt, 2003; Kavakli & Gero, 2001). However, they may not realize that undergraduate students do not use drawings to engage with content constructively and participate in mediated discourse as effectively as professionals do.

In sum, the results suggest that drawing prompts that target disciplinary practices to draw on paper can hinder students' learning outcomes by reducing students' cognitive engagement and participation in discourse. On a theoretical level, Study 2 showed that disciplinary practices may build on cognitive and sociocultural processes, as suggested by my framework (Figure 2.1). To engage in disciplinary practices, students may require support to engage in more general cognitive and sociocultural learning processes, such as engaging with new content (generative learning) and using drawings to discuss concepts with their peers (mediated discourse). On a practical level, Study 2 showed that instructors may not provide enough support to help students use their drawings. The instructors in Study 2 expected that students can engage with drawings as professionals do. Hence, in the classroom, students may require drawing prompts carefully designed to help students engage with drawings by providing support for cognitive and sociocultural processes. I test the effects of drawing prompts that support multiple learning processes in Study 3.

**Limitations of Study 2.** The findings of this study should be interpreted in light of the following limitations. First, I conducted a quasi-experiment in the classroom context, which limits valid causal inferences because non-random differences between conditions and unmeasured differences may have affected the results. Hence, an experiment with random assignment of individuals to conditions should replicate the results.

Second, this quasi-experiment investigated whether prompts provided to introduce an educational technology were more effective than a control condition without prompts or the technology. I did not include a control condition that used the same prompts without an educational technology or an educational technology without the prompts. Therefore, I cannot make inferences about the effectiveness of prompts independent of the educational technology.

Third, I only assessed spatial skills using a test of mental rotation to account for students' difficulties in learning the chemistry content, as documented in prior work (Hegarty & Waller, 2005; Stieff, 2007). However, other spatial skills may also affect students' ability to learn with models or drawings. Hence, future work should include additional tests of spatial skills, particularly those related to drawing, to identify potential aptitude-treatment factors.

Fourth, I did not assess whether the drawing and modeling prompts supported cognitive processes such as self-regulation and mental model integration, as in Study 1. Self-regulation in terms of enhanced efficiency is difficult to measure when students collaborate in the classroom context. Differences in instructional time may not necessarily reflect time spent learning, but include time spent coordinating tasks between partners or waiting for help from an instructor. Mental model integration in terms of enhanced mental models is also difficult to measure when students collaborate. Individual students may not draw and reflect on their own mental models, but those of their partners. In Study 3, I address this limitation by asking students to submit their own drawings to assess their mental models.

Fifth, the representations of isomers used in this study, especially the wedge-dash drawing, has been shown to be particularly difficult for students (Barrett et al., 2014). It is possible that focusing students on better representations may help them learn more from engaging in drawing prompts. For instance, if prompts asked students to work together to design their own representation of an isomer as a drawing in line with the learning process of mediated discourse, they may benefit more from planning drawings on paper. In Study 3, I will address this limitation by asking students work with peers to generate their own ideas on paper and build upon them.

Finally, while my results suggest that differences in how students engaged in drawing or modeling might account at least in part for my findings, I did not directly measure how students engaged with each disciplinary practice. Study 2 only collected interview data from instructors, and the interviews suggest that their perceptions may not precisely match the experience of students. In order to better understand students' learning processes, Study 3 examines their drawings and problem-solving strategies to determine how students engage in disciplinary practices through repeated drawing prompts in a semester-long course.

# Chapter 5

## Study 3: Investigating Drawing Prompts that Support Multiple Learning Processes[5]

Study 3 examines the effects of drawing prompts that target multiple learning processes in a semester-long engineering course. Observations of this course prior to intervention showed that instructors used drawings in class each week to explain visual-spatial concepts and emphasize drawing as a valued disciplinary practice. Hence, this course provided an opportunity to provide prompts *repeatedly* in alignment with the instructional goals of an authentic course in another STEM discipline, which extends Studies 1 and 2. In this engineering course, I implemented drawing prompts that supported disciplinary practices by demonstrating how engineers draw to solve problems and asking students to draw in a similar way. Further, the prompts provided specific support on what and when to draw as students engage with content. Particularly, the prompts targeted multiple cognitive and sociocultural processes that may help support disciplinary practices, as suggested in Study 2, particularly generative learning, spatial cognition, and mediated discourse.

In this study, students received drawing prompts in an educational technology as they solved problems about engineering concepts throughout a semester. Hence, in the following, I first provide a background on how engineering professionals and students solve problems. Then, I discuss the effects of drawing prompts for multiple learning processes that aim to help students learn how to solve problems using drawings. Results from this study will provide insights into the effectiveness of drawing prompts that combine multiple learning processes across theoretical perspectives and show how students engaged with drawing over a semester-long course.

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[5] A manuscript of this work is available at: Wu, S. P. W., Van Veen, B., & Rau, M. A. (under review). How drawing prompts can enhance conceptual understanding and increase student engagement in a flipped engineering course. *Journal of Engineering Education*.

## Background

Studies of professional engineers show that they solve disciplinary problems *conceptually* by first translating the problem into a visual-spatial drawing that helps them *qualitatively* "see" and reason with the content (McCracken & Newstetter, 2001). The drawing serves as a model of the problem and depicts structural relations among the underlying concepts (de Vries & Scheiter, 2012; Schwarz et al., 2009). Then, engineers review and evaluate their drawing by *quantitatively* applying formulas or using a calculation tool to determine numerical parameters, which then helps them revise their drawing (Kothiyal et al., 2016).

In contrast to professionals, novice engineering students tend to solve problems *procedurally* using a "plug-and-chug" method in which they immediately apply a formula or algorithm to given problems as a mindless procedure of meaningless symbol manipulation (Bergqvist, 2007; Lithner, 2003). In doing so, they may not engage with the underlying concepts and their structural relations (Bergsten, Engelbrecht, & Kågesten, 2017; Higley, Litzinger, Van Meter, & Masters, 2007). Furthermore, they may not develop the disciplinary practices of engineers who use drawing as a valued conceptual problem-solving strategy (de Vere et al., 2011; McCracken & Newstetter, 2001).

Students' tendency to use formulas procedurally may stem from *instructional practices* in engineering, especially in introductory-level courses. In such courses, engineering instructors help students build a foundation of knowledge by defining relevant concepts, deriving formulas, and demonstrating how to apply concepts and formulas (Litzinger et al., 2011; Streveler, Litzinger, Miller, & Steif, 2008). However, these instructional practices have been found to overly emphasize procedural quantitative skills and algorithmic thinking (Brint et al., 2008; Litzinger et al., 2011; Nelson Laird, Shoup, Kuh, & Schwarz, 2008). Students can excel in these courses by memorizing and applying formulas procedurally for exams or homework problems (Bergqvist, 2007; Lithner, 2003).

To address this issue, engineering education research suggests that "when mathematical knowledge is being recontextualised to engineering subjects or engineering design, a conceptual approach to mathematics is more essential than a procedural approach" (Bergsten et al., 2017, p. 550). Engineering instructors propose using a minimal-mathematical approach that relies on drawings and models to help students engage with the underlying concepts through "insight" of structural relations (Otung, 2001). This work aligns with mathematics education research, which suggests that visual-spatial representation of problems can enhance conceptual problem solving (Rittle-Johnson, Siegler, & Alibali, 2001). Yet, little work has focused on how to support conceptual problem solving for undergraduate engineering students through instructional activities (Litzinger et al., 2011; Streveler et al., 2008).

One potential solution to the plug-and-chug issue is to use drawing prompts. Drawing prompts can help students engage with structural relations and participate in the work of engineers by conceptually solving problems, as discussed in Chapter 2. Drawing prompts can be effective if they engage students in disciplinary practices, in which students use drawing as a problem-solving strategy in STEM (Ainsworth et al., 2011; Cooper et al., 2017). However, it is unclear if drawing prompts can help students engage in conceptual problem solving in a semester-long undergraduate engineering course, such that they counteract the preferred algorithmic "plug-and-chug" method.

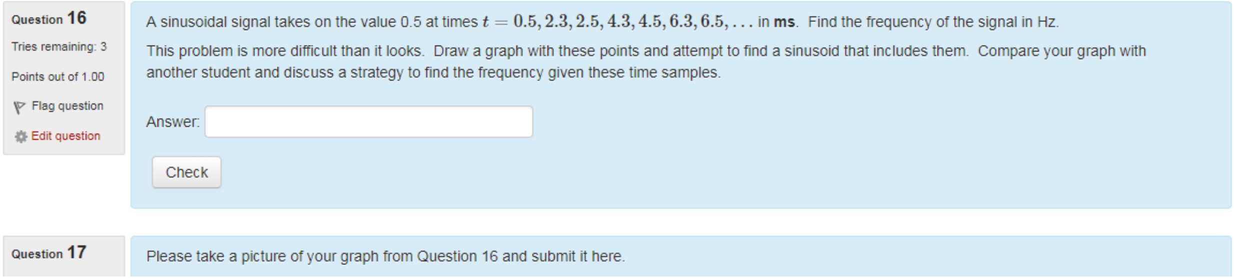
To address this gap, I implemented drawing prompts that target multiple learning processes in engineering to help undergraduate engineering students solve problems conceptually, not procedurally. Because prior work and the findings of Study 2 shows that students may need additional instructional support to engage in disciplinary practices, I provided drawing prompts at two levels. At the level of the instructor, I added prompts to lectures that demonstrate how professionals solve problems conceptually using drawings to support disciplinary practices. Further, at the level of the student, I added drawing prompts to specific engineering problems that described how students can draw to solve each specific problem. These prompts help students focus on the relevant content via generative learning, use their drawing to relate content in the problem via spatial cognition, and compare their drawings with peers via mediated discourse. To determine whether these prompts enhance students' learning outcomes, I investigate **RQ3.1**: Do drawing prompts enhance students' exam performance in an undergraduate engineering course?

Further, if the drawing prompts help students solve problems conceptually, then students should draw qualitative models of the problems as engineers do (Kothiyal et al., 2016). Yet, students often focus on solving problems quantitatively and may not draw qualitatively. Hence, I investigate the strategies used by students prompted to draw in **RQ3.2**: How do drawing prompts engage students with their drawings to solve problems?

## Method

To investigate my research questions, I conducted a quasi-experimental study with a class in Spring 2018 (*n* = 129 students) that received drawing prompts (*drawing condition*) and a class in Fall 2017 (*n* = 189 students) that did not receive prompts (business-as-usual *control condition*).

**Setting.** All students were enrolled in an introductory-level electrical engineering course on signal processing. The course was held in a technology-enhanced classroom with laptop computers, TV monitors, whiteboards, and tables that seat 3-6 students. The course was designed as a "flipped" classroom in which students watched video lectures and completed a comprehension quiz about the lecture prior to class. During the class periods, students solved engineering problems in an educational technology as described below.



A sinusoidal signal takes on the value 0.5 at times $t = 0.5, 2.3, 2.5, 4.3, 4.5, 6.3, 6.5, \ldots$ in **ms**. Find the frequency of the signal in Hz.

This problem is more difficult than it looks. Draw a graph with these points and attempt to find a sinusoid that includes them. Compare your graph with another student and discuss a strategy to find the frequency given these time samples.

Answer:

Please take a picture of your graph from Question 16 and submit it here.

*Figure 5.1.* Example in-class problem with a prompt to draw a diagram, circled in green. This example problem (Question 16) asked students to submit their diagram in Question 17.

**Educational technology.** During each class period, students in both conditions used an educational technology to complete problem sets on the electrical engineering topic covered in video lectures. For each problem, students inputted a numerical answer and received correctness feedback for up to three attempts. Students were encouraged to work with peers at their table to solve problems. While students solved problems, the instructional team (instructor, teaching assistant, and three undergraduate peer coaches) answered student questions.

**Drawing prompts**. Students in the drawing condition received drawing prompts at two levels. At the level of instructor, students received drawing prompts in video lectures that demonstrated how professionals draw to “see” concepts and solve specific engineering problems. In the video, the instructor encouraged students to draw if they solve similar problems. By contrast, students in the control condition received video lectures that demonstrated how to derive and apply formulas to solve the same engineering problems without explicit encouragement to draw, which supports generative learning by helping students engage with the content.

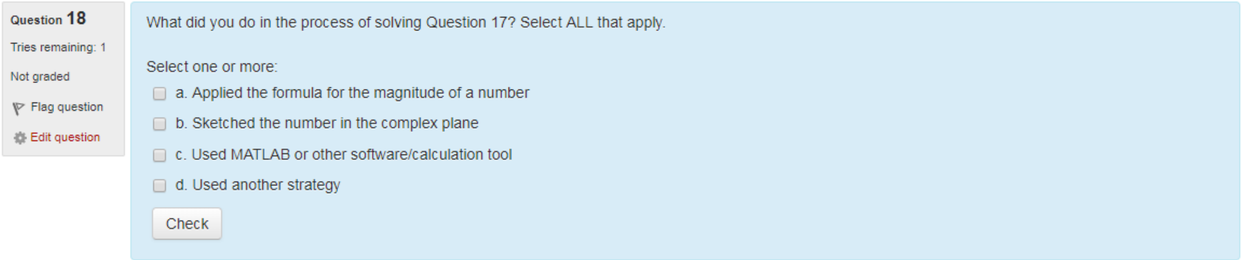
At the level of the student, drawing prompts were embedded within engineering problems to help students in the drawing condition solve problems, as shown in Figure 5.1. The prompts were provided immediately after the problem text. Each prompt asked students to draw a diagram using the specific information provided in the problem (generative learning) and relate the information in their drawing (spatial cognition). Further, it asked students to share their drawing with peers to discuss how to solve the problem (mediated discourse). Prompts to collaboratively discuss ideas have been shown to promote the use of drawings (Uesaka & Manalo, 2014).

I implemented prompts at the level of the student for 14 selected problems (one in Class 2, eight in Class 4, five in Class 6) out of a total 590 problems. Problems were selected based on observations that instructors used drawing to explain these problems to students and log data from the previous semester showing poor student performance. Each problem targeted foundational concepts that help students depict electrical signals and builds on mathematics concepts typically taught in high school: trigonometric functions (Class 2 and 6) and complex numbers (Class 4). Because these are foundational concepts, students must use them to solve problems in later class periods and in future courses. In particular, prior research has shown that complex numbers in particular are a "threshold concept" in engineering education that may lead to "troublesome knowledge" for future courses (Mercorelli, 2015; Meyer & Land, 2003).

#### Assessments.

***Exams.*** I assessed learning outcomes using students' exam performance on questions that target conceptual understanding or procedural knowledge. The instructor first identified 35 exam questions that assessed students' *conceptual understanding* of underlying visual-spatial content. This set of questions was highly reliable (Cronbach's α = .796). I then identified 39 exam questions that assessed *procedural knowledge*, which were also highly reliable (Cronbach's α = .847).

***Survey.*** I assessed students' engagement with drawings using surveys that asked students to rate, among other strategies, how often they used drawing to solve problems (*1* = Never, *5* = At least 3 times a week). Surveys also collected demographic information about students' major, year in school, gender, number of prior math courses, and prior experience in a flipped class.



What did you do in the process of solving Question 17? Select ALL that apply.

Select one or more:

☐ a. Applied the formula for the magnitude of a number
☐ b. Sketched the number in the complex plane
☐ c. Used MATLAB or other software/calculation tool
☐ d. Used another strategy

*Figure 5.2*. Example strategy checkbox asking students how they solved a specific problem. Students select from four choices: applying a formula, sketching (drawing), using a calculation tool, or another strategy.

***Strategy checkboxes.*** I assessed problem-solving strategies by asking students in the drawing condition to indicate how they solved a selected set of problems with drawing prompts or problems in which the instructor expected students to solve the problem with drawing. Specifically, students responded to multiple-choice questions in the educational technology, as shown in Figure 5.2, asking: “What did you do in the process of solving Question [#]?” Students selected all that apply from four strategies: applying a formula, drawing, using a computation tool, or using another strategy. For the last problem with a drawing prompt that I implemented in Class 6, I added an open-ended question that asked students to state if they drew and explain why or why not.

***Drawings.*** I assessed use of drawings by coding all submitted drawings for accuracy/completeness, qualitative approach, and quantitative approach. The coding scheme for these three categories by problem is shown in Appendix B. Two independent coders graded 10-12% of each set of drawings; grading was reliable for each set (*ICC*s(2, 2) > 0.733, Shrout & Fleiss, 1979).

**Procedure**. As shown in Table 5.2, the class involved three midterm exams, spaced evenly across 26 class periods, and a final at the end of the course. In Fall 2017, students in the control condition received one existing drawing prompt during Class 18 and responded to a survey in Class 25 near the end of the semester. In Spring 2018, students in the drawing condition provided survey data at three time points in the semester: a pre-survey at the beginning, a mid-survey at the first midterm, and a post-survey in Class 25 to match the timing of the survey in Fall 2017. I added drawing prompts to Class 2, 4, and 6, prior to the first midterm. In addition, I collected drawing data in Class 2, 4, and 9 (during the midterm) and strategy checkbox data in Class 4, 5, 6, and 18.

Table 5.2
*Overview of Study 2 procedure over the semester for the control and drawing conditions.*

| | **Class Period** | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** | **11** | **12** | **13** | **14** | **15** | **16** | **17** | **18** | **19** | **20** | **21** | **22** | **23** | **24** | **25** | **26** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Control** | Drawing Prompt | | | | | | | | | | | | | | | | | | ■ | | | | | | | | |
| **(N = 189)** | Survey | | | | | | | | | | | | | | | | | | | | | | | | | Post | |
| | Survey | Pre | | | | | | | | Mid | | | | | | | | | | | | | | | | Post | |
| **Drawing** | Drawing prompt | | ■ | | ■ | | ■ | | | | | | | | | | | | ■ | | | | | | | | |
| **(N = 129)** | Drawings | | ■ | | ■ | | | | | ■ | | | | | | | | | | | | | | | | | |
| | Strategy checkbox | | | | ■ | ■ | ■ | | | | | | | | | | | | ■ | | | | | | | | |

## Results

Table 5.3
*Descriptive statistics of demographic information for the control and drawing conditions. Percentages do not add up to 100% due to missing survey data.*

| | Control condition (N = 189) | | Drawing condition (N = 129) | |
|---|---|---|---|---|
| | N | % | N | % |
| Year in School – First-year | 1 | 0.5% | 4 | 3.1% |
| Year in School – Sophomore | 70 | 37.4% | 85 | 65.4% |
| Year in School – Junior | 74 | 39.6% | 26 | 20.0% |
| Year in School – Senior | 26 | 13.8% | 6 | 4.6% |
| Gender – Male | 141 | 75.4% | 104 | 80.0% |
| Gender – Female | 29 | 15.5% | 18 | 13.8% |
| Prior experience in a flipped classroom | 122 | 65.2% | 95 | 73.1% |
| Major – Electrical/computer engineering | 154 | 82.4% | 98 | 76.0% |
| | Mean | Std. Dev. | Mean | Std. Dev. |
| Prior math courses taken | 4.0 | 1.3 | 4.3 | 1.5 |

**Prior checks**. First, I checked for prior differences between conditions. Table 5.3 shows descriptive statistics of survey data for both cohorts. A MANOVA with condition as the independent factor and students' major (electrical/computer engineering majors vs. non-majors), year in school, gender, number of prior math courses, and prior experience in a flipped class (flipped experience) as dependent measures showed significant differences in year, $F(1, 267) = 21.884$, $p = .000$, p. $\eta^2 = .076$, and flipped experience, $F(1, 267) = 6.403$, $p = .012$, p. $\eta^2 = .023$. Students in the control condition had more years in school and less prior experience in a flipped class, compared to students in drawing condition. Hence, I include year and flipped experience as covariates in the analyses below.

Next, I checked for missing data and found 43 students with missing data ($n$ = 19 in the control condition and $n$ = 23 in the drawing condition). Missing data analyses show significant differences between students with and without missing data between conditions, $F(1, 314) = 5.038$, $p = .025$, and reported use of drawing, $F(1, 295) = 5.270$, $p = .022$. There were no significant differences on demographics or exam performance, $p$s > .05.

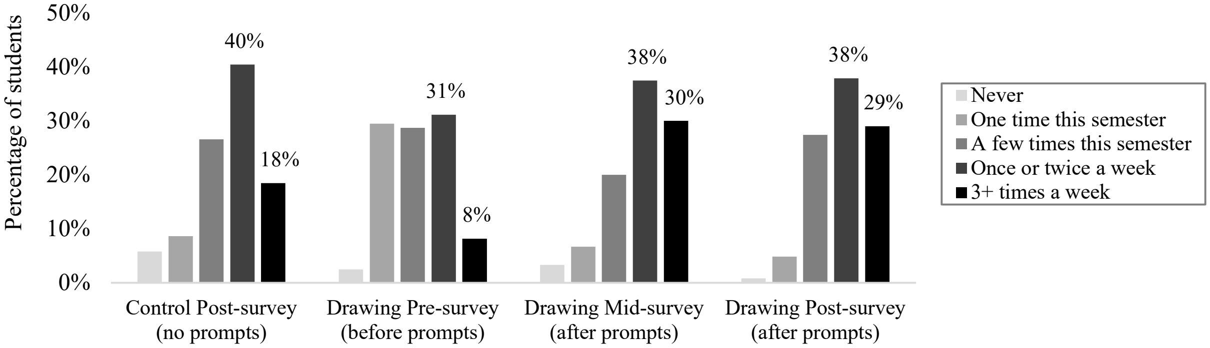


*Figure 5.3*. Students' reported drawing use on surveys, conducted over two semesters.

Finally, to ensure that drawing prompts affected students' engagement with drawing, I checked for differences in the frequency of reported drawing use between students who responded to the survey in the control condition ($n$ = 173; 92.0%) and students who responded to the post-survey in the drawing condition ($n$ = 124; 96.1%). Recall that both surveys were conducted at the end of the semester in Class 25. Because survey results were not normally distributed (see Figure 5.3), I conducted a Mann-Whitney U test to compare the two conditions. The result showed a higher frequency of drawing use, $U = 9076$, $p = .018$, for the drawing condition ($M = 3.9$, $SD = 0.9$) than the control condition ($M = 3.6$, $SD = 1.1$). Further, I compared differences in student engagement with drawing over time for the students in the drawing condition who completed all three surveys ($n$ = 106; 82.2%). A repeated-measures ANOVA with survey time (pre-survey, mid-survey, post-survey) as the independent factor and reported drawing use as dependent measures showed a main effect of drawing use, $F(2, 104) = 19.299$, $p = .000$, $\eta_p^2 = .271$. Compared to the pre-survey ($M = 3.104$, $SD = 1.077$), students reported drawing more at the mid-survey ($M = 3.821$, $SD = 1.058$) and post-survey ($M = 3.840$, $SD = .907$).

**Differences in learning outcomes**. To investigate **RQ3.1** (whether drawing prompts enhanced exam performance), I conducted ANCOVAs with score on exam questions (conceptual or procedural) as the dependent measure, condition as the independent measure, and year and flipped experience as covariates. On conceptual understanding, the results showed a main effect of condition, $F(1, 273) = 5.572$, $p = .019$, $\eta_p^2 = .020$, such that the drawing condition ($M = 89.7\%$, $SD = 7.6\%$) outperformed the control condition ($M = 86.9\%$, $SD = 10.4\%$). On procedural knowledge, results showed no significant differences between condition, $F(1, 273) = 1.424$, $p = .234$. That is, exam performance on procedural knowledge did not differ between the drawing condition ($M = 90.7\%$, $SD = 7.7\%$) and control condition ($M = 89.9\%$, $SD = 7.9\%$).

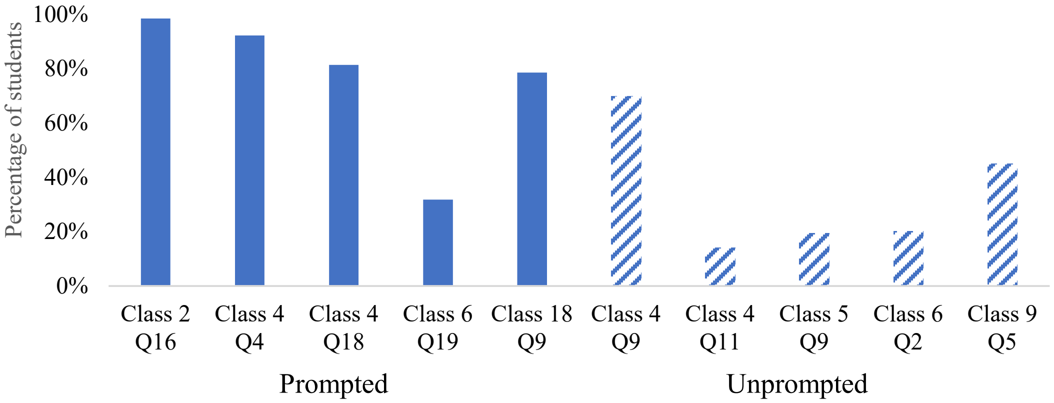


*Figure 5.4*. Percentage of student who respond on strategy checkboxes that they used drawing to solve a given problem, organized by problems that include a drawing prompt (left, in solid blue) and problems that did not include a drawing prompt (right, in blue stripes).

***Differences in problem-solving strategies.*** To investigate **RQ3.2** (how drawing prompts engage students with drawings to solve problems), I qualitatively examined student responses to strategy checkboxes and the drawings for students in the drawing condition ($n = 129$).

As shown in Figure 5.4, responses to strategy checkboxes showed that an overall higher percentage of students drawing for problems with drawing prompts than for unprompted problems. Most students reported using drawing as a problem-solving strategy (78.6%-98.5%), except for Class 6 (31.8%). In Class 6, recall that I asked students to explain why they did or did not draw. Student responses are shown in Table 5.4. Students who drew stated that drawing helped them visualize the concepts and use as a tool to solve the specific problem. The students who did not draw explained that they could visualize the concept in their own heads, drawing took too much time or effort, or they did not know how to draw to solve the problem.

Table 5.4

*Student responses to an open-ended question on whether and why they drew in Class 6. Bold added for emphasis.*

| **Did you draw?** | **Why or why not?** |
|---|---|
| Yes<br>(*n* = 41) | “Yes I have and it is extremely helpful for **visualizing the problems**.”<br>“I sketched it after missing something once or twice. Felt like I **needed the learning tool** after that.” |
| No<br>(*n* = 84) | “Nope. Wouldve **taken too long**”<br>“I **dont think I would be able to graph an accurate enough graph** to help me.”<br>“No. I **didnt have a pencil** on me. I could **just visualize the 4 points in my head**. I acknowledge though that it wouldve been better had I drawn it out.”<br>“No because it was **possible to do the questions without sketching** X(f) and I **wasnt totally sure how to sketch it**.”<br>“No i did not sketch, I was **able to picture it just using the equations**”<br>“no, mostly because I **wasnt able to initially sketch X(f)** but once I answered the first couple of questions, I was only **kinda able to visualize it**. Plus I am **extremely awful at sketching**” |

In line with the variation in the student responses from the strategy checkboxes, the drawing data suggest that students did not always use their drawings to solve problems. As shown in Figure 5.5, some students generated incorrect or incomplete drawings (7%-23%). Further, while some students used a formula or calculator to solve the given problem (11%-49%), rather than using their drawing as a qualitative model from which they solved the problem (23%-70%). The variability in when students choose to solve problems quantitatively or qualitatively may stem from differences in difficulty for each specific problem: More students used their drawing for easier problems such as adding/subtracting phasors in Class 4 (70%) than for harder problems such as multiplying/dividing phasors in Class 4 (23%). Further, students did not use drawing to solve similar problems. For example, when asked to add phasors in Class 4 and 9, more students drew in Class 4 when prompted (70%) than in Class 9 when unprompted (45%). This suggests that students who used their drawing in Class 4 chose to use formulas instead in Class 9, even when solving a similar problem.

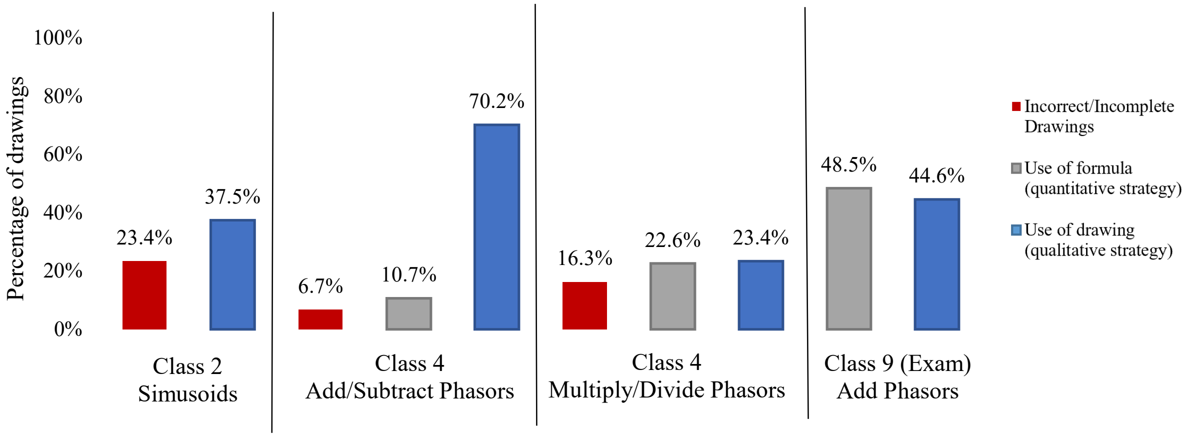


*Figure 5.5*. Percentage of students' drawings that were incorrect/incomplete (in red), showed use of formulas (in grey), or use of drawings (in blue) to solve the problem, organized by class period and type of problem.

## Discussion

This study investigated the effects of drawing prompts that combine multiple learning processes to help students conceptually solve problems in an undergraduate engineering course. Quantitative results showed that students who received drawing prompts showed enhanced conceptual exam performance, when compared to students who did not receive prompts (**RQ3.1**). Drawing prompts did not affect procedural knowledge, in line with prior research on generative learning and findings in Studies 1 and 2 (Leutner & Schmeck, 2014; Van Meter & Garner, 2005). Qualitative results showed that drawing prompts increased students' use of drawing (**RQ3.2**). Yet, the results also suggest that students did not always draw qualitative models to conceptually solve problems but may use formulas or calculations to quantitatively solve problems instead.

In this study, drawing prompts may have enhanced conceptual understanding because they engaged students in multiple learning processes: disciplinary practices, generative learning, spatial cognition, and mediated discourse. This finding aligns with my framework in Figure 2.1, which suggests that disciplinary practices rely upon other processes from the cognitive and sociocultural perspective (see Chapter 2). Particularly, students in this study may have benefited from the drawing prompts at the level of the student, which directed students on what and when to draw. These prompts may help them engage in generative learning to depict relevant content in their drawings and in spatial cognition to identify underlying structural relations. Further, the fact that drawing prompts asked students to draw when solving specific problems may engage students in mediated discourse to share and discuss drawings collaboratively. Without explicit support for multiple processes, students may not engage in disciplinary practices, as found for students who received drawing prompts in Study 2. Hence, my findings suggest that students may require drawing prompts that not only demonstrate how to draw as a disciplinary practice, but also guide students on what and when to draw in order to help them engage in multiple learning processes.

The additional support increased students' use of drawing and seemed to engage students with their drawings overall. However, there was some variability in when students chose to draw and how students use their drawings. Students were more likely to draw when prompted, but they sometimes chose to not draw because they found drawing too difficult, time-consuming, or unnecessary. As some students reported, they visualized the problem in their heads and then use formulas to solve the problem. This strategy may be effective because it aligns with the disciplinary practice of engineers who draw as a qualitative strategy to visualize the given problem and then use quantitative strategies to evaluate their drawing (Kothiyal et al., 2016). However, the choice to visualize, but not draw, may reduce students' ability to engage in sociocultural processes where they collaborate with peers to make meaning of features in their drawing (mediated discourse). These students may still engage in cognitive processes where they increase constructive engagement with content by engaging with formulas (generative learning), but they may not engage in other cognitive and sociocultural processes that support disciplinary practices.

In sum, the results suggest that repeated drawing prompts for multiple learning processes can help students learn content and engage with their drawings in an engineering course. On a theoretical level, the findings provide evidence for the effectiveness of drawing prompts that combine multiple learning processes across theoretical perspectives. On a practical level, findings show how students engaged with and perceived the role of drawing as they learned content over a semester-long course. Students may use two different problem-solving strategies that align with disciplinary practices, which I aim to investigate with two types of drawing prompts in Study 4.

**Limitations of Study 3.** The findings of this study should be interpreted in light of the following limitations. First, this study builds upon Studies 1 and 2, which focused on a different STEM domain. It is possible that the effects of drawing prompts are stronger in engineering than in chemistry due to differences in the nature of the content and the context of the classrooms. Future work should test the effects of repeated drawing prompts that target multiple learning processes in chemistry and other STEM domains to determine if these results translate across domains.

Second, unmeasured differences between classes may explain differences between conditions (e.g., different motivations, collaboration routines). I was able to control for differences in demographics across different semesters, but an experiment with random assignment of students to conditions is needed to control for other possible unmeasured effects. To this end, I conducted Study 4, an experiment that assigned students in one classroom to two groups that each received different types of drawing prompts.

Finally, my studies have not directly compared drawing prompts that target different sets of learning processes to identify which combinations of learning processes best support disciplinary practices. My qualitative analyses suggest that the process of disciplinary practices does not rely on all cognitive and sociocultural processes, but specific combinations of processes may optimally help students engage with the content as professionals do. Specifically, students seem to engage with drawing as a disciplinary practice in two ways: as a qualitative model that helps them solve problems with their community (in line with mediated discourse) and as a qualitative model that they can relate to quantitative formulas (in line with spatial cognition). To determine the effects of these two problem-solving strategies, Study 4 investigates drawing prompts that target two disciplinary practices: a qualitative strategy that focuses on drawing via sociocultural processes vs. a quantitative strategy that focuses on translating drawings to formulas via cognitive and sociocultural processes.

# Chapter 6

## Study 4: Comparing Two Types of Support for Disciplinary Practices in Drawing Prompts

To address the gaps identified in Study 3, Study 4 investigates two types of drawing prompts for disciplinary practices that focused on drawings or formulas to help students solve engineering problems. Prompts for drawings focus on a qualitative strategy, which helps students engage with relevant features in their drawing, discuss these features with peers, and use drawings to model problems as professionals do. Particularly, these prompts target mediated discourse and disciplinary practices from the sociocultural perspective to help students engage with their drawing through participating in valued practices with their learning community. Drawing prompts for formulas focus on connecting a qualitative to quantitative strategy, which helps students translate aspects of their drawings to formulas, direct their attention to relevant numbers, and evaluate their solutions as professionals do. Particularly, these prompts target spatial cognition and disciplinary practices from the cognitive and sociocultural perspectives respectively to help students translate specific features in drawings to other practices that help them solve problems.

In this study, engineering students solve problems with drawing prompts that either focus on qualitative drawings or quantitative formulas in the semester-long course described in Study 3. Below, I first discuss how the two types of drawing prompts can promote qualitative or quantitative strategies that support conceptual understanding. Then, I discuss findings on which type of prompt is more effective for undergraduate students and how students engaged with drawings to solve problems. Results will identify which type of support best facilitates disciplinary practices and how drawing prompts that target different combinations of learning processes engage novice undergraduate students with content in the engineering classroom.

### Background

As discussed in Study 3, professional engineers often draw qualitative models and then apply quantitative formulas to conceptually solve disciplinary problems (Kothiyal et al., 2016; McCracken & Newstetter, 2001). However, students prefer to procedurally “plug-and-chug” numbers into formulas (Bergqvist, 2007; Lithner, 2003). To address this issue, I implemented drawing prompts in Study 3 to help students conceptually solve problems. I found that the prompts were effective and that students engage with these drawing prompts in two different ways. Some students used their drawing a qualitative model while others translated their drawings to a quantitative formula. To determine how best to support conceptual problem solving, I investigate two types of drawing prompts that either focus on qualitative drawings or quantitative formulas.

Drawing prompts for *qualitative models* may be effective by helping students use their drawings to solve problems conceptually. Prior research on mediated discourse (see Chapter 2), which primarily focuses on how students discuss drawings with others, suggests that students struggle to relate features and make meaning of concepts shown in their drawing. Hence, students may benefit from prompts that provide specific cues regarding what features to focus on (e.g., axes, patterns) and guidance on how to “read” their drawing to engage with the content (e.g., extrapolate a trend, predict a resultant). Such additional support from drawing prompts may help students, such as those in Study 3 who did not focus on drawings, use drawings as qualitative models and engage in conceptual problem solving (Kothiyal et al., 2016).

Alternatively, drawing prompts for *quantitative formulas* may be effective if they help students solve engineering problems conceptually via translating drawings to formulas. This strategy aligns with the disciplinary practices of engineers, who first draw to generate a qualitative model and then use formulas to generate a quantitative solution (Kothiyal et al., 2016). Formulas are essential to engineering because, like drawings, formulas provide a model of how concepts relate to one another using symbols and mathematical operators. To use formulas successfully, students must identify the appropriate problem space by using the given information in a problem and then choose and apply the appropriate formula (Tall, 2008). Because drawings show how information relates to one another, drawings can help students identify the problem space as well as relevant formulas, numbers, and operations. That is, if students can translate relations depicted in drawings to identify and use the appropriate formulas, they can engage in conceptual problem solving with formulas. Hence, focusing on quantitative formulas provide an opportunity for students to engage in spatial cognition processes, in which students make sense of structural relations. Because formulas are provided to students, this strategy does not require cognitive learning processes of mental model integration or the sociocultural process of mediated discourse, where students negotiate and revise their drawings with peers. Hence, the use of formulas may decrease the demands of the drawing task. In Study 3, the video lectures primarily focused on how to use drawings rather than apply formulas, so students did not receive support on how to translate between drawings and formulas. To this end, providing drawing prompts that focus on formulas may enhance conceptual understanding if they first ask students to draw the underlying concepts and then help students use their drawing to apply the appropriate formulas for the given problem.

Both practices that focus on qualitative drawings and quantitative formulas can help students engage in the disciplinary practices of engineering professionals (Kothiyal et al., 2016; McCracken & Newstetter, 2001), but it is unclear which practice drawing prompts should support in order to help undergraduate students solve engineering problems conceptually. Drawing prompts that focus on *qualitative drawings* may enhance students' conceptual understanding of the underlying concepts by helping students make meaning of relevant relations in their drawings qualitatively. Alternatively, drawing prompts that focus on *quantitative formulas* may help students enhance conceptual understanding by making sense of information from qualitative drawings to solve problems quantitatively with formulas.

From prior work and from the instructor perspective, it is unclear if drawing prompts should focus on qualitative drawings or on quantitative formulas. In planning meetings, the engineering instructors stated that students should develop both practices. The instructors regularly engaged with drawings and formulas in their work but did not provide additional instructional support on either practice. Thus, an experiment is needed to test the two strategies in order to determine whether they are effective in enhancing students' learning outcomes. To this end, I investigate **RQ4.1**: Are drawing prompts focused on qualitative drawings or on quantitative formulas more effective in enhancing students' exam performance?

Further, it is unclear whether the additional support focused on qualitative drawings or quantitative formulas will help students engage in disciplinary practices as professionals do. Although drawing prompts are designed to help students use their drawings to solve problems, Study 3 showed that students may not do so effectively. Students may require drawing-focused qualitative prompts to help them engage with their drawing. By contrast, formula-focused quantitative prompts aim to help students translate between qualitative and quantitative problem solving. However, students may focus solely on quantitative methods and plug-and-chug numbers procedurally because students commonly use formulas without qualitative models. Hence, it is unclear how prompts focused on drawings or formulas may affect students' choices to use (or not use) qualitative and quantitative problem-solving strategies. To understand potential mechanisms underlying the effects of the prompts, I investigate **RQ4.2**: How do students engage with drawings and formulas to solve problems, as a result of qualitative or quantitative drawing prompts?

## Method

**Experimental design.** To investigate these research questions, I conducted an experiment with the Fall 2018 cohort of students (*n* = 126) enrolled in the flipped electrical engineering course on signal processing described in Study 3. All students received materials implemented in the Study 3 drawing condition. That is, they watched video lectures that emphasized how professionals draw to solve problems and completed problem sets with the assistance of peers and an instructional team (instructor, teaching assistant, and five undergraduate coaches).

In this quasi-experiment, I randomly assigned students to two conditions by tables in the classroom: 14 tables to the qualitative condition (*n* = 66) and 12 tables to the quantitative condition (*n* = 60). Recall that the course is held in a technology-enhanced classroom where students sit at tables of 3-6 to solve problems in an educational technology. Students must individually enter answers into the educational technology, but they are encouraged to work with peers. In the first three weeks of the course, I collected students' seat locations. Further, I observed student interactions to check for students who interacted with peers across table groups.

**Drawing prompts**. Students in both conditions received drawing prompts for 13 problems, as implemented in Study 3 (eight in Class 4, five in Class 6). Due to technical issues, students in this study did not receive different sets of drawing prompts for one problem in Class 2.

For each of the 13 problems, students received up to three drawing prompts that provided guidance on how to use their drawings qualitatively or formulas quantitatively to solve the problem. All students received a drawing prompt that followed the problem statement. After each wrong attempt in the educational technology, students may receive up to two additional review prompts. Each additional prompt provided progressively more specific support on how to use their drawings qualitatively or how to use formulas quantitatively to solve the problem. Specifically, the *qualitative condition* received up to three drawing-focused qualitative prompts that helped students determine what features in their drawings to focus on and how they can use their drawing to solve the problem. The *quantitative condition* received up to three formula-focused quantitative prompts that helped students determine what givens and operations to focus on as well as direct students to apply the appropriate formula. See Table 4.1 for example prompts. The course instructors provided feedback on the content of the prompts for each problem.

Table 4.1
*Example qualitative and quantitative prompts. Differences between prompts are underlined.*

| **Prompt** | **Qualitative prompts** | **Quantitative prompts** |
|---|---|---|
| Class 4, Question 6: *Adding Phasors* | | |
| *Drawing Prompt* | Solve the problems graphically - not using your calculator - based on what you've learned about adding, subtracting, multiplying, and dividing complex numbers.<br>• For addition and subtraction, use the head-tail method to draw the resulting phasors.<br>• For multiplication and subtraction, use magnitudes and phases to find the resulting phasors. | Solve the problems graphically - not using your calculator - based on what you've learned about adding, subtracting, multiplying, and dividing complex numbers.<br>• For addition and subtraction, use the rectangular form of x and z to find the resulting phasors.<br>• For multiplication and subtraction, use the polar form of x and z to find the resulting phasors. |
| *Review Prompt #1* | On your graph:<br>• Draw the vector x + z using head-tail addition of vectors<br>• Use the location of x + z to estimate Re{x + z}<br>• Double-check the units of the real and imaginary axes | On your graph:<br>• Approximate the values of Re{x} and Re{z}<br>• Use your approximated Re{x} and Re{z} to find Re{x + z}<br>• Double-check the units of the real and imaginary axes |
| *Review Prompt #2* | On your graph:<br>• Draw the tail of z at x and then draw the vector z from that point (head-tail addition of vectors)<br>• Project x + z down to the Re axis to estimate Re{x + z}<br>• Check that Re{x + z} is between Re{x} and Re{z} on the real axis<br>• Double-check the units of the real and imaginary axes | On your graph:<br>• Project x and z to the Re axis to approximate the values of Re{x} and Re{z}<br>• Add Re{x} and Re{z} to find Re{x + z}<br>• Check that the value of Re{x + z} is slightly negative on the real axis<br>• Double-check the units of the real and imaginary axes |

| Period 6, Question 18: *Multiplying sinusoids* | | |
|---|---|---|
| *Generate Prompt* | • First, use the Euler decomposition for the cosine to find the sum of sinusoids and sketch the frequencies on a spectrum<br>• Then, modulate the signal by shifting each frequency by f2<br>• Sketch (yes, draw it on paper!) X(f) to answer the following questions. | • First, use the Euler expansion to find the sum of sinusoids (in the first set of parentheses)<br>• Second, modulate the signal by multiplying sinusoids to find the product (remember to FOIL)<br>• Third, draw all positive and negative frequencies of modulated signal on a frequency spectrum. |
| *Review Prompt #1* | 1) Add phasors<br>• Use the Euler decomposition for the cosine to represent the sum of sinusoids<br>• Sketch all positive and negative frequencies on a frequency spectrum<br>2) Modulate the signal<br>• Modulate the signal by shifting each frequency by f2<br>• Sketch the sum and difference frequencies in X(f) | 1) Add phasors<br>• Use the Euler decomposition for the cosine to represent the sum of sinusoids<br>• Check that you have both positive and negative frequencies<br>2) Modulate the signal/Multiply phasors<br>• Modulate the signal by multiplying the sinusoids using the Euler representation (remember to FOIL)<br>• Sketch all positive and negative frequencies of the product in X(f) |
| *Review Prompt #2* | 1) Add phasors<br>• Use the Euler decomposition for the cosine to represent the sum of sinusoids (see lecture video on The Spectrum: Representing Signals as a Function of Frequency)<br>• Sketch the four positive and negative frequencies on a frequency spectrum<br>2) Modulate the signal<br>• Modulate the signal by adding and subtracting f2 from each frequency (see lecture video on Multiplication of Sinusoids)<br>• Sketch the sum and difference frequencies on a new frequency spectrum, X(f) (there should be eight total) | 1) Add phasors<br>• Use the Euler decomposition for the cosine to represent the sum of sinusoids (see lecture video on The Spectrum: Representing Signals as a Function of Frequency)<br>• Check that you have four frequencies (two negative and two positive)<br>2) Modulate the signal/Multiply phasors<br>• Modulate the signal by multiplying the sinusoids using the Euler representation (remember to FOIL; see lecture video on Multiplication of Sinusoids)<br>• Sketch the resultant positive and negative frequencies of the product in X(f) (there should be eight total) |

**Procedure**. This study replicates the procedure of the drawing condition in Study 3, except that students received prompts that correspond to their condition in Class 4 and 6. I collected survey data at three time points (pre-survey, mid-survey, post-survey), drawing data, and strategy checkbox data. Further, I assessed student's exam performance using the conceptual and procedural exam questions as described in Study 3. Both the conceptual exam and procedural exam were highly reliable (Cronbach's $\alpha = .849$ and .830, respectively).

## Results

**Manipulation checks**. As in Study 3, I first checked for demographic differences between conditions and differences in missing survey data.

Table 6.2
*Descriptive statistics of demographics for the qualitative and quantitative conditions. Percentages do not add up to 100% due to missing survey data.*

| | Qualitative condition ($N = 66$) | | Quantitative condition ($N = 60$) | |
|---|---|---|---|---|
| | N | % | N | % |
| Year in School – Sophomore | 40 | 60.6% | 31 | 51.7% |
| Year in School – Junior | 13 | 19.7% | 19 | 31.7% |
| Year in School – Senior | 7 | 10.6% | 1 | 1.7% |
| Gender – Male | 53 | 80.3% | 41 | 68.3% |
| Gender – Female | 8 | 12.1% | 9 | 15.0% |
| Prior experience in a flipped classroom | 46 | 69.7% | 35 | 58.3% |
| Major – Electrical/computer engineering | 57 | 86.4% | 47 | 78.3% |
| | Mean | Std. Dev. | Mean | Std. Dev. |
| Number of prior math courses taken | 3.9 | 1.1 | 4.0 | 1.4 |

First, I checked for differences in demographics between conditions, as shown in Table 6.2. A MANOVA with condition as the independent factor and students' major (electrical/computer engineering majors vs. non-majors), year in school, gender, number of prior math courses, and prior experience in a flipped class (flipped experience) as dependent measures showed no significant differences between conditions, *p*s > .05.

Second, I checked for students with missing survey data ($n = 47$; $n = 23$ in the qualitative condition and $n = 24$ in the quantitative condition). Missing survey data analyses show no significant differences in demographics or exam performance, *p*s > .05.

In this study, I additionally checked implementation fidelity by examining if students sat at different tables and worked with students in a different condition. Observations showed that students did not work with peers across tables. However, I identified 72 students who sat at different tables over the first three weeks ($n = 38$ in the qualitative condition and $n = 34$ in the quantitative condition). In the following analyses, I present results for all students as well as for students who did not move between tables.

Table 6.3
*Means and standard deviations (in parentheses) for conceptual and procedural exam questions by condition and student groups (all students and all students who did not change tables).*

| | All students | | Students who did not change tables | |
|---|---|---|---|---|
| | Qualitative ($n = 66$) | Quantitative ($n = 60$) | Qualitative ($n = 28$) | Quantitative ($n = 26$) |
| Conceptual Exam Questions | 85.5%<br>(11.3%) | 87.1%<br>(10.4%) | 83.7%<br>(10.5%) | 90.1%<br>(6.5%) |
| Procedural Exam Questions | 90.3%<br>(7.9%) | 91.1%<br>(8.0%) | 89.1%<br>(8.1%) | 91.9%<br>(6.2%) |

**Differences in exam performance.** To investigate **RQ4.1** (whether prompts focused on drawing or formulas are more effective in enhancing exam performance), I analyzed the effects of the prompts on conceptual and procedural exam performance, as in Study 3. Means and standard deviations of students' exam scores are shown in Table 6.3.

On conceptual understanding, an independent t-test with condition as the independent measure and score on conceptual exam questions as the dependent measure showed no significant differences between condition, $t(1, 124) = .806$, $p = .422$. However, for students who did not move between tables, there was a main effect of condition, *t*(1, 52) = 2.650, *p* = .011, *d* = .733, such that the quantitative condition outperformed the qualitative condition.

On procedural knowledge, the same independent t-test with score on conceptual exam questions as the dependent measure showed no significant differences between conditions, *t*(1, 124) = .324, *p* = .746, as found in Study 3. For students who did not move between tables, there was also no significant difference between conditions, *t*(1, 52) = 1.427, *p* = .159.

**Differences in problem-solving strategies.** To investigate **RQ4.2** (how students engage with drawings and formulas to solve problems), I examined students' responses to surveys, responses to strategy checkboxes, and submitted drawings.

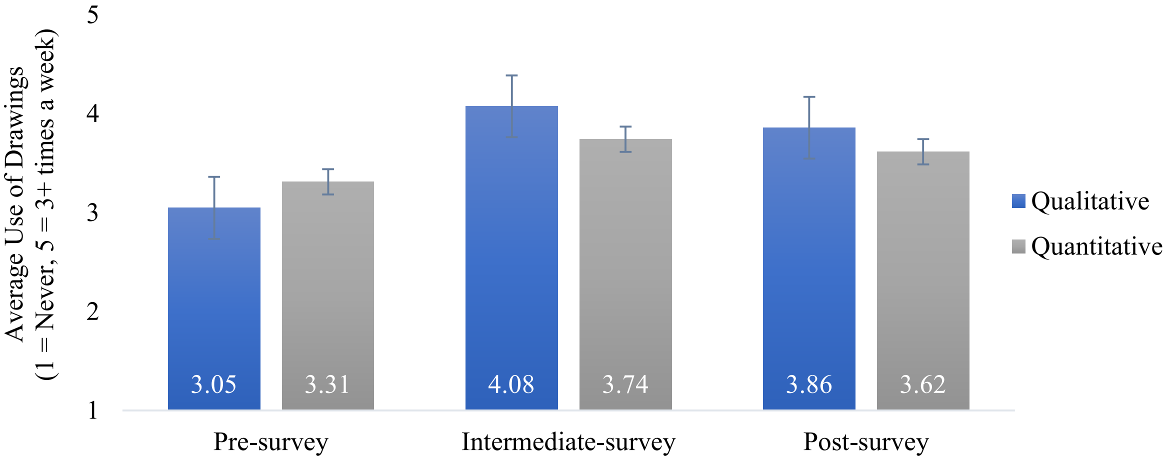


*Figure 6.1*. Average reported use of drawing on surveys by survey time and condition.

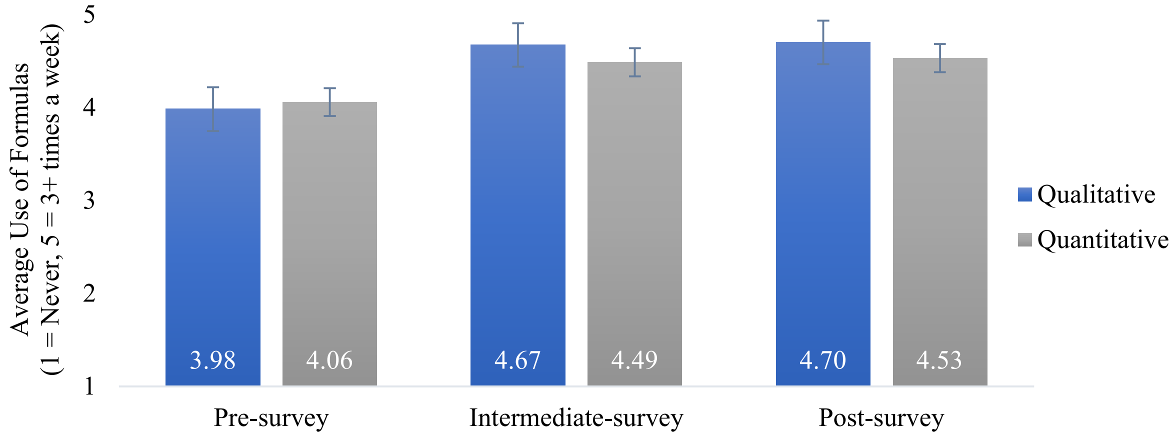


*Figure 6.1*. Average reported use of formulas on surveys by survey time and condition.

First, I analyzed *survey data* for differences in students' use of formula and drawings from the pre-, intermediate-, and post-survey ($n$ = 85; 45 in the qualitative condition and 40 in the quantitative condition). Figures 6.1 and 6.2 show average reported use of drawings and formulas respectively, by survey time and condition. Repeated-measures ANOVAs with average use of strategies (drawing, formula) as the dependent measure and condition as the independent factor showed an interaction of condition with drawing use, $F(2, 82) = 6.067$, $p = .003$, p. $\eta^2 = .129$, such that only the qualitative condition showed significant increases in drawing use from the pre-survey to the intermediate-survey and post-surveys, $F(2, 82) = 22.259$, $p < .001$, p. $\eta^2 = .352$. There was no significant effect on formula use, $F(2, 82) = 3.088$, $p = .051$, p. $\eta^2 = .070$. For students who did not move between tables ($n$ = 34 students; 19 in the qualitative condition, 15 in the quantitative condition), there were no significant effects on drawing use $F(2, 31) = 1.924$, $p = .163$, or formula use, $F(2, 31) = 2.163$, $p = .132$.

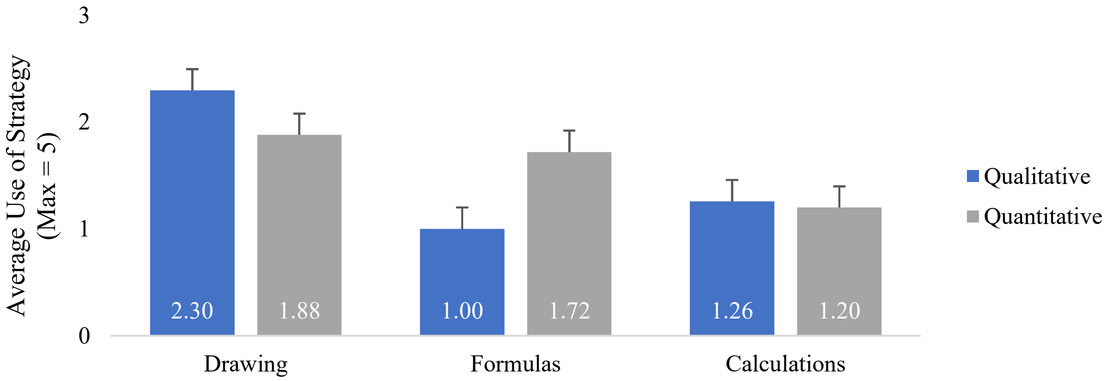


*Figure 6.3*. Average reported use of drawing, formulas, and calculations on strategy checkboxes by condition.

Second, I explored differences in students' problem-solving strategies on five in-class problems for which students responded to *strategy checkboxes* ($n$ = 116; 63 in the qualitative condition, 53 in the quantitative condition). Figure 6.3 shows the use of drawings, formulas, or calculations to solve problems by condition. Independent t-tests with condition as the independent factor and strategy use (drawings, formulas, calculations) as the dependent measure showed that students in both conditions reported similar use of drawings, $t(1, 114) = .893$, $p = .374$, and calculations, $t(1, 114) = .362$, $p = .718$, to solve the targeted problems. However, students in the quantitative condition were more likely to use formulas than students in the qualitative condition, $t(1, 114) = 3.193$, $p = .002$, $d = .585$.

A similar pattern emerges for students who did not move between tables ($n = 52$ students; 27 in the qualitative condition, 25 in the quantitative condition). Students in the qualitative and quantitative condition reported similar use of drawings, $t(1, 50) = 1.142$, $p = .259$, and calculations, $t(1, 50) = .174$, $p = .862$. However, students in the quantitative condition were more likely to use formulas than students in the qualitative condition, $t(1, 50) = 2.568$, $p = .013$, $d = .711$.

Table 6.4
*Problem-solving strategies identified in student drawings, organized by condition and problem.*

| | Condition | Class 2 Problem 16 *Sinusoids* | Class 4 Problem 8 *Adding/ subtracting phasors* | Class 4 Problem 11 *Multiplying/ dividing phasors* | Class 9 Exam 1 *Adding phasors* (unprompted) |
|---|---|---|---|---|---|
| Incorrect/ incomplete drawings | Qualitative | 12 | 12 | 44 | 7 |
| | Quantitative | 11 | 11 | 36 | 10 |
| Use of a *qualitative* strategy | Qualitative | 53 | 46 | 11 | 31 |
| | Quantitative | 43 | 32 | 6 | 18 |
| Use of a *quantitative* strategy | Qualitative | 0 | 2 | 5 | 18 |
| | Quantitative | 3 | 6 | 7 | 15 |

Lastly, I analyzed students' *drawings* for differences between conditions regarding incorrect/inaccurate drawings and drawings that use a qualitative or quantitative approach. As shown in Table 6.4, students in the qualitative condition seemed to use drawings as a qualitative strategy more so than students in the quantitative condition. However, several patterns emerge for both conditions. First, when students are not prompted to draw in Class 9 Exam 1, they are likely to use their drawing as a quantitative strategy, even though they solved a similar problem using qualitative strategies in Class 4 Problem 8. Second, students were less likely to generate correct or complete drawings for certain problems, such as Class 4 Problem 11 even though they drew and used qualitative strategies in Problem 8 during the same class period.

Table 6.5
*Example student responses to an open-ended question on whether and why they drew in Class 6. Bold added for emphasis.*

| **Did you draw?** | **Why or why not?** |
|---|---|
| Yes<br>(*n* = 66) | “Yes! It was **helpful for representing** how the frequency values "slid to the right," and also made it easier to **keep track of which values belonged where**.”<br>“Yes, I did just to be able to **pair an image with the math that was behind it**, the problem became easier to solve.”<br>“I started without a sketch and then **used one since I didnt quite understand** how to get [questions] 20 and 22”<br>“I **drew a rough sketch** and only used it to answer question 23”<br>“Yes, **I did it to follow instructions** however it did not help me in solving the problem. **I trust my math more than I trust my graphing** so Id rather put more effort into checking my math than drawing a graph wrong.” |
| No<br>(*n* = 60) | “no, i **just used the equations**”<br>“No I did not. **I do not know how to sketch any of this** so I guessed”<br>“I did not sketch the graph. I **simply expanded the terms and found the needed values within**.”<br>“No, did not want to spend time on a sketch when **I can see the frequency and phase values in my equation**.”<br>“No, I wrote out the equations and used foil. That is easier to me than drawing it out.”<br>“No, I was able to see the graph by imagining it, and **the numbers make sense to me visually**.”<br>“No I did not sketch X(f), **no time**. Need to complete exercise.”<br>“No. Other than the fact that it wouldve **taken a long time with my awful artistic skills**, I simply **set it up as eulers formula**, so that i could easily see which frequencies were the largest/smallest.” |

To understand how and when students chose to draw, I qualitatively explored students’ responses to an open-ended question in Class 6 in which they explained why they did or did not draw. Example student responses are shown in Table 6.5. Students who drew stated that drawing helped them visualize the values or the math, but some of these students also mentioned only drawing sometimes and not trusting their own drawings. Students who did not draw stated that they instead imagined the graph in their heads, used math to solve the problem, and worried about not having enough time, especially because they believe they had poor artistic/visual skills.

### Discussion

This experiment compared the effects of drawing prompts that focused on quantitative formulas vs. qualitative drawings. Results showed that students who received prompts for quantitative formulas outperformed students who received prompts for qualitative drawings on conceptual exam questions, but only for students who did not move between tables (**RQ4.1**). Because students were assigned to conditions by table groups, the effect of the prompts may have been reduced for students who moved between tables and thus may have engaged with students who used different strategies. Overall, I found that prompts for both conditions seemed to increase students' use of the targeted strategy (**RQ4.2**). However, students also engaged in quantitative and qualitative strategies, regardless of their assigned condition.

The findings suggest that students benefit from *quantitative* support that helps them translate from qualitative drawings to quantitative formulas, rather than *qualitative* support that only focuses on identifying relations in drawings. The quantitative support may help students engage with content conceptually, rather than procedurally, via two cognitive and sociocultural processes. First, students may engage in a cognitive process (spatial cognition) to make sense of features depicted in drawings and then identify relations in formulas (e.g., points composed of real and imaginary values relate to sine and cosine functions). Second, students may engage in a sociocultural process (disciplinary practices) of translating between drawings and formulas, as used by engineering professionals (Kothiyal et al., 2016; McCracken & Newstetter, 2001). Translation is crucial because professionals often use multiple representations to solve problems

(Ainsworth, 2006a; Kozma, Chin, Russell, & Marx, 2000; Nathan et al., 2013). My findings align with the surprising result from Study 2, which showed that translating between models and drawings was more effective than focusing on paper drawings alone. Translating between drawing and other disciplinary practices may help students further engage with the content. Taken together, this work suggests that drawing prompts should also support other disciplinary practices in addition to drawing and particularly focus on how to help students translate between them.

My findings also extend prior research on problem solving in mathematics education, which has compared the effects of students' use of quantitative and qualitative approaches in interview studies (Acevedo Nistal, Van Dooren, & Verschaffel, 2012b; David, Roh, & Sellers, 2018). For instance, a study on functions in calculus showed that students who focus on points on a graph as quantitative numerical *values* outperformed students who focus on qualitative spatial *locations* (David et al., 2018). This study argued that location-thinking may lead students to treat points as objects, which result in confusion about the x and y values that underlie the point. This study was the first to investigate how students think about points on a graph and proposed that different results may emerge when targeting different content, such as understanding spatial relationships and geometry. My study provided evidence that, even when focusing on spatial relationships on graphs, the quantitative approach is more effective than the qualitative approach, in the context of problem solving for novice undergraduate engineering students.

Regarding the prompts that focused on drawing as a qualitative strategy, I expected that these prompts would help students learn content via sociocultural processes, particularly mediated discourse and disciplinary practices. However, both learning processes may require skills that novice undergraduate students may not yet have developed. For instance, mediated discourse engages students in generating and negotiating their own drawings to make meaning of how features show content. However, because students reported that they do not trust their own drawings, they may be unwilling to discuss features in their drawings with other novices. Further, because students do not know what to draw, discussions with other peers may focus on irrelevant features depicted in students' drawings. In contrast, professionals often "see" underlying structural relations that go beyond the features shown in a drawing, which allows them to ignore irrelevant surface features in discussions (Casakin & Goldschmidt, 1999; Harré, Bossomaier, & Snyder, 2012; Jee et al., 2014). This difference between novices and professionals may lead instructors to assume that students can focus on relevant features and participate in mediated discourse and disciplinary practices as they do, in line with the findings in Study 2. For instance, instructors may only discuss the location of points on a graph as a way to help students relate the points and ask students to discuss locations with their peers. However, as found in the interview study discussed above regarding how students think about points in calculus, students may then view points as locations or static objects that they can procedurally manipulate, without understanding the underlying x and y values (David et al., 2018; Moore, 2016). Hence, novice engineering students may require additional support, such as immediate feedback on whether they included relevant features in their drawings, to effectively participate in discourse with peers and use their drawings to qualitatively solve problems as professionals do.

I only found significant differences between the drawing and formula conditions for students who did not move between tables. This result suggests that collaboration may play a role in how students engaged with the prompts and supported each other in learning the content. Students who did not move between tables may establish collaboration patterns in how they solved problems together. For example, a group of students in the formula-focused quantitative condition may have one or two students who draw a graph while others give feedback and review formulas that may apply to the problem. This collaboration pattern may reduce the difficulty of generating a drawing and help students identify errors, which then leads to the revision of drawings. As discussed in Chapter 2, evaluating and revising drawings (not just constructing drawings) are important processes in disciplinary practices. Hence, the collaborative drawing process may help students better engage with their drawings. In contrast, students who moved between tables may work independently without collaboration routines because they are unfamiliar with other students at their new table. In this case, they may only compare drawings with peers at the end, which can result in more errors in their drawings and less continued support from their peers as they engage with concepts. These students may also choose to not draw and compare drawings with other students because all students work on problems at their own pace. Because participation in disciplinary practices often involves collaboration to help professionals evaluate, revise, and use content shown in drawings, further research should consider the effects of collaboration routines and how groups of students use drawings in classrooms.

Overall, my results on students' engagement showed that the qualitative prompts seemed to increase students' use of drawing while quantitative prompts seemed to increase students' use of formulas. Survey data showed that the qualitative condition reported higher use of drawing in the middle and end of the semester, compared to the quantitative condition. Moreover, the quantitative condition reported higher use of formulas for targeted in-class problems than the qualitative condition. This difference may indicate that students in the qualitative condition are overall using drawing as a strategy more often, but they may not be using drawing effectively. In contrast, students in the quantitative condition used formulas to solve targeted conceptual problems.

Other factors may also play a role in how students chose to solve problems, as shown by the variation in students' strategies across problems in the drawing data. Those who learned the qualitative approach may switch to the quantitative approach and vice versa. They may also choose to not use either strategy for specific problems. Such variation in problem-solving strategies seem to result from two decision factors, efficiency and intuitiveness, which have been recently identified in the mathematics education literature (Brown, Menendez, & Alibali, 2018). Interview studies show that, for new problems, novice students find quantitative approaches more intuitive and thus they prefer this method, even if it is less computationally efficient (Acevedo Nistal, Van Dooren, & Verschaffel, 2012a; Brown et al., 2018). In line with this work, my drawing data shows that students chose to draw as a qualitative strategy when it was easy to draw and they were prompted to do so, but when it was difficult to draw, they either did not draw or drew incorrectly. When asked to explain why they did or did not draw, students who drew reported that it helped them visualize the problem (in line with the intuitive factor) while students who did not draw reported that drawing took time and effort (in line with the efficiency factor). This finding provides insight into the complex factors that contribute to how and when students choose to engage with drawings in a classroom setting, even when they are prompted to engage in specific strategies.

On a theoretical level, this study suggests that students benefit from drawing prompts that combine learning processes from the cognitive and sociocultural perspectives, particularly the cognitive process of spatial cognition with the sociocultural process of disciplinary practices. In contrast, focusing on sociocultural processes only (mediated discourse and disciplinary practices) may not help novice students identify and use content effectively to solve problems. It is possible that sociocultural processes rely on knowledge and skills that professionals have developed over time, which explains why prior research on disciplinary practices has primarily focused on professionals (see Chapter 2). This suggests prior work such as the RCA framework (Prain & Tytler, 2012), which only addresses mediated discourse and disciplinary practices from the sociocultural perspectives, may not apply to novice undergraduate students, unless it additionally includes learning processes from the cognitive perspective. In combination with Studies 2 and 3, this study suggests that the cognitive and sociocultural processes may complement one another in providing different types of support that help students engage with drawing to solve problems.

On a practical level, this study showed that students benefit from support that helps them translate from qualitative drawings to quantitative formulas when they solve problems in an undergraduate classroom. Further, I showed that students vary in their problem-solving strategies due to individual differences, targeted problems, and differences in collaboration routines in a classroom setting. Additional research should further identify factors that contribute to productive problem-solving strategies and investigate how student engage with drawings, peers, and content to engage in disciplinary practices. Future work should test different combinations and dosages of instructional support in drawing prompts to determine how best to help students engage with their drawings to learn STEM content.

**Limitations of Study 4.** The findings of this study should be interpreted in light of the following limitations. First, participants of this study were students enrolled in one electrical engineering course. Specific characteristics of the students or the course may have contributed to the effects of drawing prompts in this study. Hence, future work should test whether the findings hold in other courses and with other populations of students.

Second, this study randomly assigned students to conditions by table. Although observations in Study 3 showed that students typically did not move between tables, the students in this study did move. Further, results showed that only the students who did not move between tables benefited from quantitative prompts, which suggests that sustained collaboration between peers may affect how students engaged with drawing prompts. Further studies should directly measure students' collaboration to determine how students who did and did not move between tables engage with different types of prompts and worked with their peers to solve problems.

Third, students in this study may benefit from quantitative prompts because they must provide final answers to problems as *exact* values. Qualitative prompts that focus on drawings may be appropriate in other courses where students solve problems with qualitative, *approximate* values. The focus on exact values may explain students' "trust" in math and numbers. Students may be reluctant to focus on drawings to solve problems because it can lead them to approximate answers that are incorrect, according to the technology used in this course. Additional work should examine the effects of qualitative and quantitative prompts in other STEM courses with different goals, particularly those that focus on students' qualitative understanding of content.

Fourth, I found that students did not always use the strategy that aligned with their condition. Some students may prefer one strategy or may be resistant to certain strategies. More work should investigate whether students' choices benefit or hinder their learning and how to help students choose the optimal strategy. For instance, additional interviews with students can examine why students chose their strategy and how they used it to solve problems. Such interviews can also inform the interpretation of students' drawings and which learning processes they engaged in.

Finally, this study only compared the effects of drawing prompts for disciplinary practices that also supported another sociocultural process (mediated discourse) or a specific cognitive process (spatial cognition). It is possible that supporting additional cognitive processes or different combinations of cognitive and sociocultural processes may yield different results. Additional work should test different combinations of multiple learning processes across theoretical perspectives to determine how best to enhance students' engagement and learning through drawing prompts.

# Chapter 7

## Conclusion

### Summary of Chapters

As discussed in Chapter 1, this dissertation investigates whether and how drawing prompts can help students learn visual-spatial content in STEM. To this end, I reviewed prior research in Chapter 2, which suggests that drawing prompts can help students learn content through six learning processes that have been investigated in separate lines of research from the cognitive and sociocultural perspectives. I synthesized these six processes in a theoretical framework that describes how specific processes, particularly from the sociocultural perspective, build upon more general processes, particularly from the cognitive perspective (Figure 2.1). I then tested this framework in four studies that investigate the effects of drawing prompts by combining different sets of learning processes. Each study examined the effects of drawing prompts on learning outcomes and students' engagement with content.

First, Study 1 investigated whether drawing prompts that combined three learning processes from the cognitive perspective help students learn chemistry concepts in the laboratory. To this end, I targeted a specific cognitive process (mental model integration), using an initial prompt that asked students to first generate a drawing and then revise prompts that asked students to revise their drawing. In addition to improved mental models (in accordance with mental model integration processes), I tested whether these drawing prompts enhanced efficiency (in accordance with self-regulation processes) and effectiveness (in accordance with generative learning processes). Quantitative results showed that drawing prompts enhanced efficiency. Further, drawing prompts were efficient and effective after a delay, when provided repeatedly throughout instruction. Qualitative results showed that the quality of students' drawings improved if they received repeated prompts throughout instruction. The findings suggest that drawing prompts can support multiple learning processes from the cognitive perspective through targeting a specific cognitive learning process. Further, findings suggest that prompts should help students not only generate drawings, but also iteratively revise their drawings.

Second, Study 2 examined the effects of drawing prompts for a sociocultural process (disciplinary practices) in the chemistry classroom, by comparing them to modeling prompts that focus students on orienting physical models, another disciplinary practice promoted by instructors. Quantitative results showed that drawing prompts were not effective, when compared to business-as-usual and modeling prompts. In contrast to my results, instructors stated that they would implement more drawing prompts. The findings suggest that instructors may not recognize that students struggle to engage with drawing on paper as professionals do. Hence, the students may require more support for additional learning processes to engage in disciplinary practices.

Third, Study 3 investigated the effects of drawing prompts that combined support for multiple learning processes across the cognitive and sociocultural perspectives in an engineering course. Specifically, I compared a cohort of students in an engineering course who received drawing prompts in lectures and in practice problems to a cohort of students who did not receive prompts. Quantitative results showed that drawing prompts were effective in enhancing exam performance on conceptual questions. Qualitative results showed that students did not always use drawings to solve problems, but sometimes relied on other strategies. Findings suggest that students benefit from drawing prompts that support multiple learning processes, but they may still need more instructional support on how to use their drawings to solve problems.

Finally, Study 4 investigated the effects of two different types of drawing prompts that support two different sets of learning processes in the engineering classroom. Qualitative drawing prompts helped students use and discuss features in their drawings to solve problems, in line with prior work on mediated discourse. Quantitative drawing prompts helped students translate their drawings to formulas, in line with prior work on spatial cognition. Results on learning outcomes showed that quantitative drawing prompts that focused on formulas were more effective than qualitative drawing prompts that focused on drawings, if students continued working with the same peers. Results on students' engagement suggest that prompts increased students' use of the prompted strategy, but students may sometimes choose other strategies that they find more intuitive or efficient. The findings suggest that, in line with Study 2, students struggle to use drawings as professionals do. Thus, students may require drawing prompts that combine learning processes across cognitive and sociocultural perspectives to engage with drawings and learn content in STEM classrooms.

## General Discussion

Taken together, this dissertation contributes to the growing literature on how drawing prompts can help students learn STEM content (Ainsworth et al., 2011; Tippett, 2016). First, my new theoretical framework in Figure 2.1 extends prior work by showing how to combine separate lines of research that have focused on different learning processes and outcomes. My studies provide some evidence for this framework by testing whether drawing prompts that combine learning processes enhance students' learning outcomes and engagement with visual-spatial STEM content. Study 1 showed that drawing prompts can enhance learning when combining mental model integration, self-regulation, and generative learning from the cognitive perspective. Moreover, Study 3 showed that drawing prompts can enhance learning when combining multiple learning processes from the cognitive and sociocultural perspectives. These findings extend prior work, which has begun to combine multiple learning processes *within* the cognitive or sociocultural perspective (Prain & Tytler, 2012; Van Meter & Firetto, 2013), by showing how learning processes can also be combined *across* theoretical perspectives.

Particularly, I found that drawing prompts may be most effective when combining learning processes across cognitive and sociocultural perspectives. Study 2 showed that reduced learning outcomes for students who received drawing prompts that primarily focus on disciplinary practices. Further, in Study 4, I found that drawing prompts for both cognitive and sociocultural processes were more effective than prompts for sociocultural processes alone. These findings suggest that sociocultural processes may not *build upon* cognitive processes, but *rely on* them. Novice undergraduate students may need to engage in cognitive processes to make sense of their drawings before they can engage in sociocultural processes in which they use drawing as a communication and thinking tool as professionals do. Because prior work on drawing prompts has not combined learning processes across the cognitive and sociocultural perspectives, my findings propose new ways to provide support via drawing prompts and suggest a need for greater integration of research on drawing prompts across the theoretical perspectives.

My work also contributes to existing work on drawing prompts in separate lines of work, by providing insights into the effects of drawing prompts that target specific learning processes. For instance, prior work on mental model integration has primarily focused on interview studies (Duit & Treagust, 2008; Vosniadou, 1994), but not on the design of drawing prompts. Study 1 showed that designing drawing prompts that target mental model integration can be effective, when provided repeatedly to help students integrate new content in to their mental models. Further, studies 2-4 showed the effects of drawing prompts that target disciplinary practices for novice undergraduate students, which extends prior work in disciplinary practices that has primarily focused on professionals and workplace studies (de Vere et al., 2011; Ullman et al., 1990).

Finally, my findings provide practical implications on how to support novice undergraduate students who intend to pursue STEM fields so that they can begin to engage in the drawing practices of professionals in the STEM classroom. Studies 2-4 showed that students do not engage in disciplinary practices as professionals do. Importantly, the instructors in Study 2 perceived drawing prompts as valuable but did not seem to recognize that their students may have struggled to engage with drawings. Even when prompted to draw, students may not choose to engage in drawing, as found in Studies 3 and 4. Multiple factors may lead students to choose other strategies, as found in Study 4. While professionals make epistemological choices on what they draw as appropriate communication tools in the given discipline and context (Berland & Crucet, 2015; diSessa, 2004), novice students may instead choose to draw less and avoid discussions with peers for efficiency, which can reduce potential learning opportunities in the classroom. Because traditional instruction with visual-spatial content tends to focus on instructor-provided visuals (Cheng & Gilbert, 2009; Tippett, 2016), students may require additional support to draw that is typically not provided in the classroom. For instance, students may benefit from multiple opportunities to draw, as found in Study 1, and from specific guidance on what and when to draw through carefully designed drawing prompts, as found in Study 3. Hence, my findings suggest that instructors and researchers should consider not only what processes to target when designing drawing prompts, but also how to implement drawing prompts in the context of their classroom such that their students effectively engage with drawings.

In sum, my findings yield insights into the effects of drawing prompts for novice undergraduate students. By investigating the effects of different drawing prompts in the context of authentic learning environments, I identified conditions in which drawing prompts are effective and potential mechanisms underlying how drawing prompts facilitate learning of visual-spatial content. The findings show promise for drawing prompts that combine learning processes across theoretical perspectives and demonstrates the need for additional instructional support via drawing prompts in the undergraduate STEM classroom.

## Limitations and Future Directions

The findings of this dissertation should be considered in light of the following limitations. First, each study in this dissertation targeted specific types of introductory-level STEM content, and drawing prompts were designed with support of instructors involved in each study. While all studies focused on helping students learn visual-spatial content in the STEM disciplines, differences in the targeted STEM content may affect students' learning processes and outcomes. Hence, future work should investigate the effects of drawing prompts and how students engage with them when learning different types of visual-spatial STEM content.

Second, my studies address two separate STEM domains: chemistry and engineering. These domains both rely on visual-spatial content and engage students in disciplinary practices, as many other STEM domains do. However, the switch from chemistry to engineering may affect the interpretation of results across all four studies. Hence, further work should replicate my findings in both chemistry and engineering, as well as in other domains.

Third, the studies involved students enrolled in a few courses. While this allowed me to conduct more controlled experiments within a course or between sections of a course, the variance in the types of students who enroll in these classes may be small, leading to small differences in outcomes. Therefore, future work should investigate whether my findings hold with a larger population of students with varied backgrounds.

Fourth, I did not directly assess learning processes but manipulated them through the design of drawing prompts. Particularly in the classroom context, additional factors may affect how students engaged with drawing prompts. For instance, Study 4 suggests that students may choose not to engage with strategies as prompted. Hence, future work should collect additional process data to assess how and to what degree specific drawing prompts promote the targeted learning processes. Further, Study 2 suggests that classroom practices, such as whether and how students use drawing to engage and communicate with each other may affect learning outcomes. Hence, additional work should test the effects of drawing prompts that target *social* engagement in addition to sociocultural engagement.

Fifth, the studies did not address the full range of drawing activities that students may engage in to learn STEM content. Each study in this dissertation focused on helping students draw in a specific way to solve targeted problems. Hence, I did not investigate differences in factors such as creativity and specificity, which may also affect students' learning outcomes and engagement with content. For instance, some students may include more detail in drawings to help them remember the concept more vividly or use drawing to offload specific aspects of a concept that are more difficult for them, rather than draw all aspects. Further, because I only focused on novice undergraduate students, I did not investigate how to support drawing for other points in students' trajectories. For example, senior students may generate more creative and unconventional drawings, which are appropriate for open-ended design projects. These types of drawing activities may require different types of drawing prompts to help students engage with content and their drawings. Hence, future work assessing other ways in which students use drawing can provide more insight into how drawing may support learning with visual-spatial STEM content.

Lastly, my four studies did not investigate each learning process identified in Chapter 2, but each focused on relevant sets of learning processes (e.g., disciplinary practices in Studies 2-4). This approach allowed me to target specific instructional goals and align prompts with the context of each course. However, combining different sets of learning processes may yield different effects on learning outcomes and engagement, as found in Study 4. Furthermore, my studies do not isolate the separate effects of each process to identify how and when each process contributes to student outcomes. Because my framework is the first to combine multiple learning processes, it is still unknown whether and how the processes work together as depicted in Figure 2.1. Hence, future work should systematically test each combination of processes across the theoretical perspectives to determine the potential effects of drawing prompts for multiple learning processes.

## Contributions of This Work

The goal of this dissertation was to investigate how to help students learn visual-spatial STEM content through constructing their own drawings. To this end, I developed and tested a new framework that synthesized multiple learning processes from separate lines of research (Figure 2.1). My four studies identified the conditions in which drawing prompts were effective and how students engage with their drawings. In general, these findings showed that students struggled to draw and benefited from drawing prompts that combined learning processes from separate lines of work across the cognitive and sociocultural perspectives. My findings yield insights for new lines of research and practical implications for how to help novice STEM students engage in drawing as future professionals.

My findings inform future educational research on drawing prompts by showing how to combine learning processes across theoretical perspectives using my framework in Figure 2.1. Prior work has investigated the effectiveness of drawing prompts in separate lines of research within the cognitive and sociocultural perspectives, even though the two theoretical perspectives are related such that sociocultural processes supervenes cognitive processes (Nathan & Alibali, 2010; Sawyer, 2005). This suggests that researchers can potentially extend existing work on drawing prompts from the cognitive and sociocultural perspectives by combining them in accordance with my framework. As a growing field of research with contributors from multiple fields (Tippett, 2016), my findings from this dissertation helps to consolidate and expand this work.

Further, my findings suggest that drawing prompts are an effective instructional strategy that can engage students in drawing to learn content and help students use drawing as a learning strategy. Most prior work has focused on the effectiveness of drawing prompts, either by controlling whether students draw or by focusing on students who do draw (Gadgil et al., 2012; Van Meter & Garner, 2005). Yet, little work across the theoretical perspectives has considered how and when students choose to draw in the classroom setting and the effects of these choices. Students' choices of when and what to draw may demonstrate proficiency with drawing, in which their choices leverage the affordances of drawing for the specific problem they are solving, as found in the disciplinary practices of professionals (Berland & Crucet, 2015; White & Pea, 2011). Moreover, students' choices may illuminate what practices may be difficult or underutilized in STEM because of inadequate instructional support or when confusion arises for students about how and when to use drawing as a disciplinary practice.

Finally, my findings on the effectiveness of drawing prompts in two separate STEM domains, chemistry and engineering, suggest that drawing is a key STEM disciplinary practice that instructors should focus on and provide more support for. Instructors value drawing as a practice, but traditional instruction primarily focuses on helping students interpret instructor-provided visuals. Hence, instructors may not have insights into students' difficulties when drawing, as suggested by the interviews with instructors in Study 2. My findings yield some insights into how novice undergraduate students struggle to draw but instructors can support students through drawing prompts that engage them in disciplinary practices and other learning processes.

Particularly, I identified the effects of prompts that support drawing and other practices in STEM (using physical models, applying formulas) to provide some empirical evidence on which practices are effective for students and how to support students because prior work has not compared disciplinary practices (Fiorella & Zhang, 2018). This work provides practical recommendations to help instructors engage students in valued disciplinary practices and provide the necessary support that help students effectively engage in these practices.

In conclusion, my findings inform future educational research and instructional practices with drawing prompts, particularly on how to support undergraduate students in introductory-level STEM courses. I propose that drawing prompts should support multiple learning processes to help students not only use drawing as a cognitive learning strategy to engage with content, but also as a sociocultural practice to reason, problem-solve, and communicate effectively as future STEM professionals. Hence, particular attention should focus on drawing prompts and leverage their potential to engage students in professional practices and transform traditional instruction, which can further increase students' engagement and learning with content in the STEM classroom.

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