Educational Psychology Review (2019) 31:87–120
https://doi.org/10.1007/s10648-019-09467-3

REVIEW ARTICLE

How Students Learn Content in Science, Technology, Engineering, and Mathematics (STEM) Through Drawing Activities

Sally P. W. Wu[1] · **Martina A. Rau**[1]

Published online: 15 January 2019

Abstract
Recent research suggests that drawing activities can help students learn concepts in the science, technology, engineering, and mathematics (STEM) disciplines. In particular, drawing activities, which mimic the practices of STEM professionals, can help students engage with visual-spatial content. However, prior work has also shown that students struggle to learn from drawing activities. One major issue is that the learning processes underlying the effects of drawing activities are mostly unknown, and therefore, it is unclear how best to design effective drawing activities in STEM learning environments. To address this gap, our review of prior research investigates which learning processes may explain how drawing activities facilitate learning of STEM content. Specifically, we reviewed prior research across cognitive and sociocultural theoretical perspectives. We identified six learning processes fostered by drawing activities. Each learning process describes how drawing can change the way students interact with the content. Our review shows how instructional support for drawing activities that targets each learning process can enhance learning. Our findings have theoretical implications regarding how drawing activities have been studied and yield open questions about the mechanisms accounting for the effects of drawing activities on students' learning in STEM disciplines. Further, our findings suggest practical recommendations on how to effectively implement drawing activities that help students learn STEM content.

Keywords Drawing · STEM content knowledge · Visual-spatial content · Learning processes · Instructional design

✉ Sally P. W. Wu
pwwu@wisc.edu

[1] Department of Educational Psychology, University of Wisconsin–Madison, Madison, USA

Introduction

Professionals in the science, technology, engineering, and mathematics (STEM) disciplines often *draw* to reason and communicate about visual-spatial content (Arcavi 2003; Goldschmidt 1994). Drawing helps STEM professionals make sense of complex and abstract content because it allows them to externalize their thinking, make new inferences based on their drawings, and modify their drawings to examine new ideas (Arcavi 2003; Fish and Scrivener 2007; Goldschmidt 2003). Scientists have attributed the discovery of concepts such as magnetic fields and DNA structure to the process of drawing (Evagorou et al. 2015; Latour 1990; Palmer 1978). Thus, drawing practices are prevalent and are considered to be an important professional practice (Brew et al. 2012; National Research Council 2012b).

Similar to STEM professionals, STEM students may use drawing as a learning strategy to improve their understanding of visual-spatial content in STEM (Ainsworth et al. 2011; Fan 2015; Quillin and Thomas 2015). Recently, researchers have argued for the inclusion of more drawing activities alongside activities that focus on reading, writing, and speaking to align instructional practices with professional practices (Ainsworth et al. 2011; Cheng and Gilbert 2009; National Research Council 2012b). Traditionally, instructional practices in STEM have primarily focused on *providing* pre-generated visual-spatial representations to students in instructional materials such as lectures and practice problems (Rau 2017; Tippett 2016), but have rarely helped students *construct* their own drawings to learn content (Cox 1999; Van Meter and Garner 2005). Hence, students may not develop adequate drawing skills and meta-representational competencies, which describe the capacity to choose, construct, and use visual representations in relation to the task-relevant content they depict (Acevedo Nistal et al. 2012; diSessa 2004; diSessa and Sherin 2000; Hegarty 2012). The underdevelopment of such skills may hinder students' ability to learn through drawing. Indeed, prior research on student-constructed drawing activities has shown that students do not always benefit from drawing activities (Ainsworth et al. 2016; De Bock et al. 2003; Leutner et al. 2009).

To help students learn from drawing activities, we must understand through which *learning processes* drawing activities can affect learning outcomes (Lobato et al. 2014; Tippett 2016). Our review shows that separate lines of research have investigated drawing activities based on different theoretical perspectives (Davatzes et al. 2018; Leutner and Schmeck 2014; Prain and Tytler 2012; Van Meter and Garner 2005). For instance, drawing activities from the cognitive perspective may engage students in organizing and integrating relevant visual-spatial features, while drawing activities from the socio-cultural perspective may engage students in discourse with their STEM community. Drawing activities from different perspectives have addressed a variety of goals, such as translating scientific texts, increasing interest in STEM, enhancing observation skills, and representing complex phenomena (Ainsworth et al. 2011; Quillin and Thomas 2015; Van Meter and Garner 2005). To the best of our knowledge, prior research has not synthesized different lines of work on how drawing activities engage students in particular learning processes that enhance learning outcomes. The lack of synthesis has resulted in a lack of recommendations for effective designs of drawing activities.

To address these gaps, we review prior research to investigate: *What are the learning processes that drawing activities foster in order to enhance learning of STEM content* *knowledge*? This review will help close gaps in prior research on drawing activities for students and provide recommendations for effective instructional designs of drawing activities.

Our review first focuses on literature concerning learning processes and learning outcomes that drawing activities have been shown to enhance. We identified six distinct *learning processes* that explain how drawing activities enhance *learning outcomes*. The learning processes engage students with STEM content in particular ways to help students achieve specific types of learning outcomes. Organizing our review along the six learning processes allows us to suggest practical guidance for instructors to design drawing activities using a "backward design" approach. This allows instructors to identify specific learning outcomes and then design drawing activities that engage students in the learning processes that best match the targeted outcomes. Therefore, we summarize recommendations for instructional design in relation to the learning outcomes that instructors may want to promote. Finally, we conclude by discussing open questions about the potential effects of drawing activities and implications for future research.

Because our goal is to synthesize across prior literature on how drawing activities help students learn STEM content knowledge, we limit our review of the research in the following ways. First, we focus on the specific affordances of drawing activities and hence include studies that focus on drawings fully or mostly generated by students who are learning the content, not by instructors. These include studies in which students generate their own images on a blank page or "assemble" images by using components that they cut-and-paste or drag-and-drop. However, we do not include studies that focus on interpreting pre-generated drawings as the main learning outcome. Second, we focus on STEM content knowledge as the main learning outcome and thus exclude studies focused on non-cognitive outcomes (e.g., motivation, creativity, attitudes) or skill-based outcomes (e.g., laboratory skills). We also exclude studies that examine how students learn drawing skills or motor processes without a goal to enhance content knowledge. Third, we focus on learning of visual-spatial content in STEM and therefore include drawing activities that involve a visual-spatial depiction that resembles or represents an object, phenomenon, or concept in STEM. We do not include studies that exclusively focus on symbolic manipulation or diagrammatic depictions of concepts and relationships such as concept maps and schematic graphs. Fourth, we include research on drawing activities that may be used as an independent or supplemental activity within a learning environment. Finally, we include studies with students of all ages to examine possible learning processes for all students.

To identify these studies, we searched research databases for relevant articles published in journals and books, including ERIC, EBSCO, and PsychINFO, and GoogleScholar using the keywords: ("draw*" "sketch*") with ("learning" "instruction" "content knowledge") and with ("STEM" "science" "math*" "engineering" "technology"). In addition, we reviewed published and unpublished proceedings of relevant conferences, including the European Association for Research on Learning and Instruction (EARLI), the American Education Research Association (AERA), the International Conference of the Learning Sciences (ICLS), the International Conference on Computer Supported Collaborative Learning (CSCL), and the Annual Meeting of the Cognitive Science Society (CogSci). Finally, we used the "snowball" method in which we reviewed articles cited in the reference sections of relevant articles as well as citation lists of relevant articles on GoogleScholar (Greenhalgh and Peacock 2005).

Six Learning Processes Underlying How Students Learn STEM Content Through Drawing

Our review identified six distinct learning processes that emerged from different lines of research across the cognitive and sociocultural theoretical perspectives (Nathan and Sawyer 2014). As illustrated in Fig. 1, we consider this research to lie on a continuum that focuses on different learning goals, in which drawing activities 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. Our review of cognitive research identified four learning processes that are fostered by drawing activities: (1) generative learning, (2) self-regulation, (3) mental model integration, and (4) spatial cognition. Our review of sociocultural research identified two additional processes: (5) mediated discourse and (6) disciplinary practices.

In Fig. 1, we categorize the six learning processes by theoretical perspective and depict them as separate circles that build on one another. The separate circles reflect the fact that separate lines of research have investigated each learning process. Consequently, each process corresponds to different ways in which drawing activities engage students with content. Hence, we review prior research on each of the six learning processes and their respective learning outcomes in six separate subsections below.

Although separate lines of research have focused on six distinct learning processes, we propose that the processes are interrelated such that processes build on one another as illustrated by the "stacked" format in Fig. 1. We consider the processes with wider circles at the base as broader because they map to broader instructional goals, whereas the processes with narrower circles at the top are more specific in the sense that they map to more specific instructional goals. The stacked circles illustrate a major finding from our review, namely that engaging in more specific learning processes also engages students in the broader processes below it. We discuss the relationships between the processes in detail at the end of this section. There, we synthesize prior research across the different learning processes and discuss how they may build on one another. This synthesis then provides insight into how best to design drawing activities to focus on specific instructional goals, which we discuss in detail thereafter.

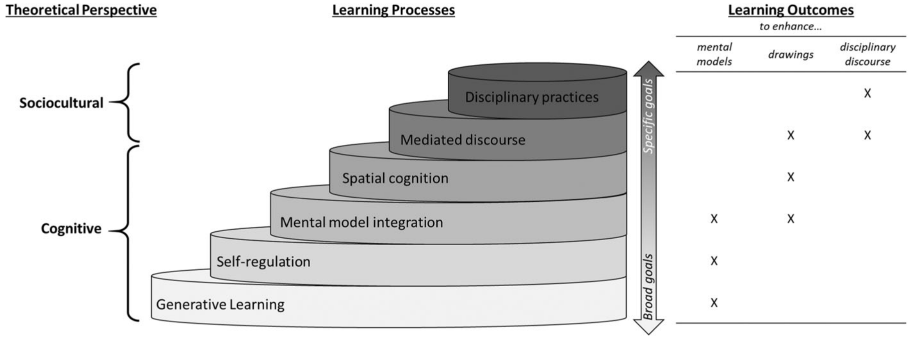

Fig. 1 Six learning processes categorized by theoretical perspectives and organized in stacked circles that illustrate a focus from broad to specific instructional goals. Each learning process enhances different types of learning outcomes, organized by their focus on mental models, drawings, and disciplinary discourse

Cognitive Processes

From a cognitive perspective, drawing is an instructional activity that can help students internally make sense of content (Chi and Wylie 2014; Leutner and Schmeck 2014; Van Meter and 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 and Wittrock 1983), which suggest that drawing activities enhance learning by increasing students' active engagement with content (Fiorella and Mayer 2015). For instance, the ICAP framework (Wylie and Chi 2014) suggests that learning increases as students engage more actively with the content. The ICAP framework considers drawing activities to be *active* if students construct a drawing without engaging with content or their prior knowledge (e.g., through 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. Experiments show that students who *constructively* generate their own drawings outperform students who *actively* trace or copy images (Gagnier et al. 2016; Mason et al. 2013). When compared to other constructive activities (e.g., summarizing text, interpreting illustrations), drawing activities have often been found to yield enhanced or comparable learning outcomes (Fiorella and Mayer 2015; Leopold and Leutner 2012), although one study found drawing to be less effective than summarizing scientific text (Leutner et al. 2009). Little prior 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 and Zhang 2018).

An advantage of drawing activities, like many other constructive activities, is that they can enhance learning of complex knowledge. Studies show that higher-order assessments of complex knowledge are more sensitive to students' conceptual learning gains than assessments of simple knowledge (Gadgil et al. 2012; Leutner and Schmeck 2014; Van Meter et al. 2006). Additionally, a few studies have shown that drawing can enhance long-term retention, even when accounting for the increased instructional time required for students to construct their own drawings (Authors 2018; Mason et al. 2013). These effects are likely a result of the increased mental effort involved in constructive engagement with the content (Sweller 2010).

Like many constructive activities, drawing activities also bear the risk of cognitive overload if they increase mental effort to an extent that hinders students from constructively engaging with the content (Schmidgall et al. 2018; Schwamborn et al. 2011). Studies suggest that drawing activities increase the perceived difficulty and mental effort of the task, which can interfere with students' learning (Schmeck et al. 2014; Schwamborn et al. 2011). Compared to activities that ask students to examine images or imagine the content, drawing activities have been shown to increase cognitive load to an extent that can exceed students' cognitive capabilities to learn the content (Leutner et al. 2009; Schmeck et al. 2014; Schwamborn et al. 2011). While increased mental effort can have positive effects if it results from deeper sense making of the content, it can also have negative effects if it results in cognitive overload.

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). This process emerges from research on multimedia learning and builds on the dual-coding theory that describes how students integrate visual and verbal information into their mental models to learn content (Mayer 2009; Schnotz 2014). Hence, the GTDC proposes that students translate verbal scientific texts into drawings in three stages. First, students select relevant information from the text to include in the drawing. Next, they organize this information spatially. Then, 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 and literature reviews based on the GTDC have documented that drawing activities engage students in these stages, which allows them to learn visual-spatial information that is verbally presented in scientific texts (Leutner and Schmeck 2014; Van Meter and 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 et al. 2014; Schmidgall et al. 2018). Further, students with higher quality drawings tend to show enhanced performance on other learning outcome tests (Leutner and Schmeck 2014; Van Meter and Garner 2005).

In sum, research on generative learning suggests that drawing activities enhance learning if they increase students' constructive engagement with content, for instance through translating content from scientific texts. The broad focus on how drawing activities can more deeply engage students with content by drawing is an important goal in each of the following processes.

Self-Regulation Recent cognitive research focuses on self-regulation and metacognitive processes that describe how students use drawing to regulate their engagement with content. Research on these processes considers students' judgments of learning and behaviors that affect how they subsequently engage with content and drawing activities (Lajoie 2008; Schraw et al. 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. Thus far, most research on self-regulation is fairly new, and there are two different views on whether and how drawing activities facilitate self-regulation processes.

First, prior work suggests that drawing activities enhance self-regulation processes by helping students self-assess and reflect on how well they understand the content (Authors 2018; Schleinschok et al. 2017; Van Meter and Firetto 2013; Zhang and Linn 2011). This view suggests that drawing allows 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 and Firetto 2013), accounts for self-regulation by building on the frameworks for self-regulated learning (Winne and Hadwin 1998) and for 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 toward 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 the self-regulated learning model (Winne and Hadwin 1998).

Second, other recent work suggests that self-regulation processes may be a prerequisite to students' benefit from drawing activities. This view suggests that differences in self-regulation processes may better explain how students engage with content, compared to mental effort from generative learning. 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). This work suggests that students do not effectively engage in self-regulation but struggle to manage how they draw content, which can hinder their learning outcomes (Schleinschok et al. 2017). Particularly, drawing activities have been shown to be difficult for novice students with low prior knowledge or who do not know how to use their drawing to engage with the content (Wu et al. 2019; Lin et al. 2016). However, even though this view suggests that students may benefit more from drawing if they receive self-regulation training, one experiment shows that drawing activities with a self-regulation training to monitor students' comprehension of content was not more effective than drawing activities without this training (Leopold and Leutner 2015).

The two views suggest that self-regulation processes may build on generative learning processes and play a key role in how students engage with content. The CTDC is the first attempt to synthesize across the two processes and specify how self-regulation may subsume generative learning. Because most research in self-regulation is fairly recent, more research should investigate to what extent drawing activities foster self-regulation or assume some level of self-regulation skills.

In sum, self-regulation research suggests that drawing activities may help students learn by focusing on the concepts that they least understand and self-regulate how they draw. However, students may also struggle to engage in self-regulation processes. The existing research on self-regulation in the context of drawing activities is relatively new. Yet, the focus on self-assessment and reflection may help students engage with their mental models and drawings, as discussed in mental model integration.

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) (Vosniadou and Brewer 1992). Misconceptions can become apparent when students are asked to draw their mental models (Harle and Towns 2013; Vosniadou and 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 and 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 (Cooper et al. 2013; Nyachwaya et al. 2014; Papaphotis and Tsaparlis 2008).

This line of research focuses on addressing gaps in students' mental models by integrating new content into them. Prior research shows that drawing activities can help students engage deeply with content to develop more sophisticated mental models that align with content and incorporate their prior knowledge (Leopold and Leutner 2012; Wang and Barrow 2011). Such effects may not be immediately visible but may be measured on delayed posttests (Authors 2018; Scheiter et al. 2017b).

To integrate content into their mental models, our review of prior research suggests that students engage in both generative learning and self-regulation processes. First, mental model integration seems to build on *generative learning processes* (Jonassen et al. 2005). When students draw, they activate their mental models by selecting relevant features and organizing them in an external, coherent structure (Scheiter et al. 2017a). The external structure helps students encode and integrate new content to their prior mental models (Kirsh 2010; Valanides et al. 2013). As a result, students may expand and revise their mental models (Duit and Treagust 2008; Vosniadou 1994).

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 and 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 and 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. Additionally, mental model integration focuses students on content shown in their drawings as an external assessment and learning tool, which is emphasized in the following processes.

Spatial Cognition Another line of cognitive research on drawing activities focuses on spatial cognition, which examines how students learn concepts through constructing and interpreting visual-spatial cues in their drawings (Authors 2018; Bobek and Tversky 2014; Cheng and 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 and Gero 2001;

Tversky 2011). In contrast to other cognitive research that primarily focuses on engagement with content or mental models, research on spatial cognition considers how students engage with drawing both as a process and a product from which they can interpret, transform, and relate visual features (Suwa et al. 2001; Tversky 2011).

Prior research on spatial cognition suggests that drawing activities can help students make sense of concepts via bottom-up and top-down visual-spatial processes (Schwartz and 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 (Tversky 2011). For example, in an unfamiliar protein model with purple and green sections, students can identify that the purple and green 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 (Latour 1990; Suwa et al. 2001). 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 and 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 and 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 and Clement 1999; Scheiter et al. 2017a; 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 as a whole (Hegarty 2004; Nyachwaya et al. 2011). While verbal descriptions allow students to vaguely describe relationships among concepts (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 and Brewer 1992). Further, drawing can amplify mental models by helping students "fill in" details that may be ambiguous in the mind (Fish and 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 and Clement 1999; Scheiter et al. 2017a; 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). Prior research shows that drawing activities can help students learn 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 and Schmeck 2014; Parnafes et al. 2012; Zhang and Linn 2011). However, prior work has not systematically tested the effects between different types of 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 and Mayer 2015; Gobert 2005; Ploetzner and Fillisch 2017).

As a further outcome, research on spatial cognition suggests that drawing activities help students develop *meta-representational competencies* through the process of constructing and identifying structural relations in drawings (Day and Goldstone 2012; diSessa 2004). Qualitative studies of students' drawings have shown that they have naïve intuitions about how to reason with drawings (diSessa 2004; diSessa and Sherin 2000). For example, primary-school children have been shown to draw relevant features and scientifically analyze their drawings for parsimony and explanatory power, which helped them refine their naïve ideas about motion (diSessa et al. 1991; diSessa and Sherin 2000). Prior research suggests that drawing activities can help students develop their meta-representational competencies, if they help students engage in specific bottom-up or top-down processes to depict content (Day and Goldstone 2012; diSessa 2004).

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. Spatial cognition relies on other cognitive processes because it engages students' mental models and builds upon their prior experience with visual representations. These processes then help students engage in sociocultural processes in which they participate in disciplinary discourse through constructing and interpreting drawings with their STEM community.

Sociocultural Processes

From a sociocultural perspective, drawing is 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.

Our review identified the RCA framework as the first to describe how students learn by drawing from a sociocultural perspective. Hence, we 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, we 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 et al. 2007; White and Pea 2011). From this perspective, students' drawings are considered a public, contextual, and developmental reflection of the social goals and context (Brooks 2009; Roth and 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 gradually depict content in drawings that conform to the visual language used in specific STEM disciplines (Brooks 2009; Enyedy 2005; Prain and 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 robust misunderstandings (diSessa and Sherin 2000; Stieff et al. 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 and 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 and 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 and Hall 1997; Nathan et al. 2007). As students draw to participate in discourse, they learn drawing practices over time that help them to make epistemological choices on what representations to draw as appropriate communication tools in the given discipline and context (Berland and Crucet 2015; diSessa 2004).

Mediated discourse processes seem to build upon spatial cognition processes, but with a particular focus on conventions used in specific disciplines. For instance, the epistemological drawing practices that result from mediated discourse resemble the development of meta-representational competencies. Both processes aim to develop the ability to choose, construct, and use drawings that help students learn specific types of content. However, prior work on mediated discourse has not focused on how students learn structural relations, and prior work on spatial cognition has not focused on students' participation in discourse using their drawings. Future work should investigate whether these processes build upon one another. If mediated discourse builds on spatial cognition processes, then this research also builds on the other cognitive processes discussed above.

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. These processes seem to build upon cognitive processes but focus on helping students make meaning of content shown in their drawings in the context of their prior knowledge, resources, and goals of their community. By gaining skills in using drawings, mediated discourse then helps students to participate in disciplinary practices.

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

This line of research considers how drawing can engage students in disciplinary practices (as learning processes) that characterize students' ability to engage with content as professionals do (as learning outcomes). Our 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 et al. 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 2012b; Schwarz et al. 2009). Drawing activities 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 et al. 2017; Evagorou et al. 2015; Fan 2015; Quillin and Thomas 2015). Prior research suggests that students engage with drawing activities in four stages: construction, use, evaluation, and revision (Quillin and 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).

Similar to scientific modeling, *design practices* in engineering and technology 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 and 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 and Gero 1998). This process refines students' ideas by providing 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.

Design practices engage professionals and students in iterative cycles of generating and revising drawings. 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 and 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 and Gero 1998). Similarly, drawing activities help students generate abstract ideas, interpret visual features depicted in their drawings, and refine drawings to transform their ideas into tangible, concrete real-world objects that can solve specific problems (de Vere et al. 2011; de Vries 2006). Qualitative studies conducted in STEM classrooms show that drawing activities can help students balance multiple design or modeling parameters, discuss structural relations in the content, compare designs, and determine how to revise their designs to solve their given problems (de Vries 2006; Nichols et al. 2013; Yang 2009).

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, in accordance with the two types of disciplinary practices described above. In *scientific modeling practices*, 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 and 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 and Russell 2005; Lehrer and 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 and Crucet 2015). In *design practices*, students must learn to create a specific, detailed design that can be built in the real world. Studies of design professionals show that they often revise their designs toward better alignment with the content and with design constraints (Goldschmidt 2003, 2014). Their designs often shift from abstract to concrete as they relate their drawing to the real world (de Vries 2006; Goldschmidt 2003). Because prior work on design practices focuses on professionals and expert-level students, it is less clear whether the drawings of novice students also shift from abstract to detailed representations of content (de Vere et al. 2011; Johri et al. 2013).

Another important outcome is the development of adaptive expertise in drawing. STEM professionals often modify and revise their designs as they relate their drawing to the real world, using their expertise in drawing that allows them to rapidly transform content for further exploration (Kothiyal et al. 2016; McCracken and Newstetter 2001; Verstijnen et al. 1998). Case studies of engineers show that they first transform problems into drawings that depict concepts qualitatively or quantitatively and then iteratively evaluate and revise transformations through drawing (Kavakli and Gero 2002; Kothiyal et al. 2016; Ullman et al. 1990). Such drawing skills play a crucial role in students' identity as STEM professionals and ability to contribute to the STEM community by using drawing to solve complex, open-ended problems (Arcavi 2003; Kothiyal et al. 2016; Kozma et al. 2000).

Disciplinary practices processes seem to build on mediated discourse processes. 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, as discussed above. Furthermore, disciplinary practices may build on the cognitive processes. For instance, in scientific modeling, the focus on revision and evaluation of models suggests that students may activate and self-assess their prior knowledge (as described in mental model integration and self-regulation) to (re)construct a coherent model of the content (Cooper et al. 2013; Leenaars et al. 2013; Wilkerson-Jerde et al. 2015). Moreover, in design practices, students and professionals "see" structural relations in their designs (as described in spatial cognition). Hence, disciplinary practices may build on mediated discourse and the cognitive processes above.

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 doing so, students seem to engage in mediated discourse and the cognitive processes discussed above.

Summary of Six Learning Processes and Their Learning Outcomes

Our review of the literature on drawing activities identified six distinct learning processes in different lines of research across the cognitive and sociocultural theoretical perspectives. Each learning process helps students learn conceptual relevant features and structural relations in STEM content. However, 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.

Yet, in describing each learning process, we found that the processes seem to build upon another, such that students engage in multiple learning processes when they engage in more specific processes. As shown in Fig. 1, processes may "stack" on top of one another such that specific processes rely upon the broad processes below it. We depict *generative learning* as a broad foundational process at the base. Its goal is to help students engage more deeply with content through translating and organizing content in a drawing. Building upon generative learning, *self-regulation* also helps students to engage with content, but further specifies how students self-assess and direct their interactions with content. Its goal is to help students reflect on their own understanding and focus their attention on relevant content. Building on the prior processes, *mental model integration* helps students engage with new content and integrate it into their mental models. Its goal is to engage students with their own mental models and revise them as needed, by activating them through generative learning processes and reflecting on them through self-regulation processes. Building on the prior processes, *spatial cognition* engages students with content by helping them clarify and identify new structural relations in their drawings. Its goal is to help students engage with their drawings as an external representation that reflects students' internal mental models and provides insights into structural relations between content. Building on the prior processes, *mediated discourse* engages students in generating, discussing, and interpreting drawings to help them participate in disciplinary discourse about the content. Its goal is to help students make meaning of how their STEM community represents content in drawings through discussion and negotiation with others. The last process, *disciplinary practices*, builds upon the prior processes to engage students in using drawings to solve specific disciplinary problems. Its goal is to help students learn how STEM professionals use drawings. Each successive "stacked" process engages students in drawing activities that help students achieve more specific learning goals.

The "stacked" relationship between the learning processes for drawing activities aligns with the broader landscape of cognitive and sociocultural research on learning, which focuses on different levels 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 entire complex systems. Coarse-grained analyses at the systemic level *supervene* on the elemental components such that any change at the systemic level necessitates a change at the elemental level (Sawyer 2005). The six learning processes we 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 broader 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. Nevertheless, these processes are interrelated and build upon one another as shown in Fig. 1.

Instructional Design of Drawing Activities

Because we found considerable overlap in learning processes and outcomes in the previous section, we synthesize instructional design recommendations for drawing activities across multiple lines of research. Our review suggests that the learning processes and outcomes overlap in how they describe students' engagement with content by focusing on different aspects of drawing activities. In line with the different units of analysis, the foci lie on a spectrum from *internal* sense-making of content within students' mental models to *external* interactions that help students engage with content within the context of their learning community. On the end of the spectrum that subsumes generative learning, self-regulation, and mental model integration, interventions primarily focus on helping students enhance their *mental models*. Through these processes, students organize and integrate content into their mental models by translating content into a drawing and reflecting on their prior knowledge with the new content. On the other end of the spectrum that subsumes mediated discourse and disciplinary practices, interventions focus on helping students engage in *disciplinary discourse*. Through these processes, students use drawings to negotiate meaning with others in their community as STEM professionals do. In addition, we found that there is considerable overlap between perspectives in the middle of the spectrum because mental model integration, spatial cognition, and mediated discourse have an additional goal to engage students with their *drawings*. To engage students in these processes, interventions ask students to use drawing as an external tool to identify relevant features, make connections between features, and learn how to convey content through drawings. Based on these three specific aspects of the drawing task focused on mental models, disciplinary discourse, and drawings, we provide specific recommendations for instructional design of drawing activities.

Drawing Activities that Engage Students with Their Mental Models

Prior research on the cognitive end of the spectrum shown in Fig. 1, particularly generative learning, self-regulation, and mental model integration, focuses on helping students build new knowledge by enhancing students' mental models and interactions with content. From this work, we identified three recommendations for the design of drawing activities.

First, research on generative learning suggests that certain types of content and instructional support can enhance students' mental models through drawing. Specifically, drawing activities should be paired with multimedia or complex visual-spatial content so that students *constructively* engage with the content, rather than *actively* (Chi and Wylie 2014). Many prior studies show that drawing activities can increase students' constructive engagement with content. For instance, drawing activities can prompt students to transform verbal text into visual-spatial drawings (Leutner and Schmeck 2014; Van Meter and Garner 2005), synthesize information across multiple pieces of content while they draw (Danish and Saleh 2014), or ask students to invent new ways of drawing to represent content (Glogger-Frey et al. 2015; Schwartz and Martin 1988).

However, because constructive engagement bears the risk of cognitive overload, instruction should reduce cognitive demands to help students focus on the targeted content (Leutner and Schmeck 2014; Van Meter and Garner 2005). Instructional support may reduce the risks of cognitive overload by removing extraneous details from the content, for instance, by reducing information about the context or aesthetic features. Much prior research has investigated instructional supports such as cutouts or a bank of features that students can cut-and-paste so that students do not focus on aesthetics of the drawing, but rather on the synthesis of how the features function and relate to one another (Schwamborn et al. 2011; Van Meter et al. 2006). However, such instructional support must not relieve students of the task of constructing content and making inferences, so that students still *constructively* engage with the content (Chi and Wylie 2014; Cromley et al. 2013). Many experiments show that drawing activities are not effective if students merely become *active* in copying visual images (Gagnier et al. 2016; Mason et al. 2013). For example, Mason et al. (2013) compared 7th grade students who were asked to draw phases of motion shown in an animation, to trace pictures of the phases, or not draw. They found that students asked to draw outperformed the other students on a test immediately after instruction and on a delayed test 2 months later.

Second, research on mental model integration suggests that drawing activities should help students (1) activate their mental models and (2) compare them to the content. Students' mental models often incorporate misconceptions that involve misapplying rules and heuristics (Cooper et al. 2010). Therefore, students need opportunities to explain and (re)construct understandings so that they identify incomplete or conflicting mental models (Cooper et al. 2013; Nyachwaya et al. 2011). To help students address misconceptions, instructional support should focus students on the relations between their own mental models and new content (Cooper et al. 2017; Duit and Treagust 2008; Vosniadou 1994). While many studies have used interviews with individual students to engage them in mental model integration, few studies have systematically investigated how best to design drawing activities to help students externalize their own mental models and integrate new content into them (Duit and Treagust 2008). We found one experiment that showed, for students who drew inaccurate mental models, prompting them to compare an expert drawing to a pre-constructed flawed drawing that matched their inaccurate mental model was more effective than prompting them to explain the expert drawing (Gadgil et al. 2012). This work suggests that simply providing an expert mental model may be insufficient. Students need to activate their own mental model and compare their flawed model to an expert model, or else they may not integrate new content into their mental model. Furthermore, some prior work suggests that if students are prompted to draw without engaging with an expert model, they may activate and reinforce their initial mental models, which are often inaccurate (Vosniadou and Brewer 1992).

Third, to help students engage deeply with content and mental models, research on self-regulation suggests that drawing activities should be *provided alongside instructional activities* to help students direct their engagement with content. For example, Zhang and Linn (2011) compared middle school students who were asked to draw while using a simulation of molecular reactions to students who received additional time with the simulation. Students who were asked to draw interacted more with their peers and with the simulation and, as a result, generated more inferences that showed more sophisticated understanding of the content. Providing drawing activities likely helps students determine what they do not yet understand in the simulation and engage with these concepts when drawing and discussing content with peers. When content is provided with drawing activities, instructional support should provide feedback to help students self-assess their progress in relation to content (Van Meter 2001; Van

Meter et al. 2006). For example, students may copy from the instructional materials to get the right answer instead of drawing to self-assess their own knowledge and reflecting on the content they do not yet understand. To address this issue, instructional support can provide continuous feedback on students' drawings or prompts to reflect on drawings. Precise, timely feedback on drawings has been shown to help students self-regulate their interactions with content in many prior studies (Sins et al. 2005; Van Meter and Garner 2005).

In sum, drawing activities that focus on mental models should engage students in organizing, self-regulating, and integrating content in relation to their (flawed) mental models. Instructional support should help students reflect on their own mental models and self-regulate their interactions with instructional content throughout the drawing task so that they engage deeply with the targeted content and revise their flawed models to align with content.

Drawing Activities that Engage Students with Disciplinary Discourse

On the sociocultural end of the spectrum, research on mediated discourse and disciplinary practices focuses on how students learn content by engaging in disciplinary discourse with their community through their drawings. From this work, we identified two recommendations for the design of drawing activities.

First, drawing activities should help students participate in the disciplinary discourse of their community. For instance, instructional designs of drawing activities can ask students to invent and revise conventions, in line with the historical development of conventions in the discipline (diSessa 2004). As mentioned above, students' initial drawings may use conventions that reflect their naïve and internally robust misunderstandings (diSessa and Sherin 2000; Stieff et al. 2011). Then, as students share and discuss their drawings with peers or instructors, they revise drawings to be more clear and explanatory (Lehrer and Schauble 2003; Nathan et al. 2007). Instructors can support this process by allotting class time for invention and revision as well as providing feedback on drawings to guide students toward adopting disciplinary conventions (Danish and Saleh 2014; diSessa et al. 1991; Wilkerson-Jerde et al. 2015). Multiple studies recommend incorporating these recommendations in two phases (Danish and Saleh 2014; Parnafes et al. 2012). First, in an open drawing phase, students construct drawings to engage with the content individually. Second, in a collaborative drawing phase, students discuss their drawings to refine their understanding. For example, Parnafes and colleagues showed that 4th–8th grade students can learn about moon phases by first individually constructing drawings about what they observe and then collaboratively revising them to understand the underlying concept of reflecting visible sunlight (Parnafes 2010; Parnafes et al. 2012).

Second, drawing activities should target specific disciplinary goals that focus on drawing at the service of communicating with the community or solving a STEM problem, rather than focusing primarily on the construction of drawings. When solving a problem, STEM professionals do not solely focus on drawing, but also on defining the problem, gathering information, evaluating possible models or designs, and revising their solutions (Atman et al. 2007; Kothiyal et al. 2016). They use drawings flexibly as thinking tools that allow them to engage in problem solving with models or designs. In contrast, students tend to focus on the aesthetic and structure of their drawings, rather than the function and behavior that the drawing conveys (de Vries 2006). If drawing activities simply ask students to draw content, they may focus on constructing drawings without understanding how to use the drawings to learn the content and solve the underlying problem. In one classroom study, middle school students who were asked to construct drawings of fractal geometric shapes and share them with their classmates spent most of their time constructing drawings because they were inspired by others' designs (Wilkerson-Jerde 2014). However, the time spent on constructing drawings left students no time to reflect on and discuss the content underlying their drawings. Hence, instruction should support reflection by allotting class time and providing support to help students process the content shown in their drawings. For example, explicit prompts can ask students to reflect on their drawings with peers so that they refine drawings to learn content and solve the given problem (Backhouse et al. 2017; de Vries 2006; Wagner et al. 2017).

In sum, drawing activities that focus on disciplinary discourse should target specific goals that help students participate in and contribute to their STEM community. Instructional support should focus on helping students engage with others in their community and address specific disciplinary problems.

Drawing Activities that Engage Students with Drawings

In the middle of the spectrum between cognitive and sociocultural theories, research on mental model integration, spatial cognition, and mediated discourse focuses on how students learn content by engaging with their drawings. From this work, we identified three recommendations for the design of drawing activities.

First, research on spatial cognition suggests that drawing activities are effective if they target specific types of structural relations that complement the content or instructional mode (e.g., static images vs. dynamic animations). For example, if the goal is to learn temporal relations from an animation (e.g., movement and change in visual features over time), drawing activities may not help students because static drawings do not allow students to easily depict dynamic temporal relations (Ploetzner and Fillisch 2017). Rather, learning about such temporal relations may be best supported by instructional activities that animate students' drawings using technologies (e.g., Chang et al. 2014; Wilkerson-Jerde et al. 2015). By contrast, if the goal is to learn causal relations from the animation (e.g., how visual features separate and recombine over time), drawing activities may be effective if they ask students to draw explanatory snapshots of an object in motion that clarify these causal relationships (Mason et al. 2013). Prior work has found that drawing activities were ineffective when designed to match a specific type of content (e.g., 2D vs. 3D representations) (Ploetzner and Fillisch 2017; Wagner et al. 2017). Our review suggests that, instead, instructors should focus on the targeted structural relations of the to-be-learned content and design drawing activities to facilitate learning of these relations. For instance, drawing activities are particularly suited for learning visual, spatial, and causal relations. Leopold and Leutner (2012) conducted 2×2 experiments that compare a drawing strategy (yes vs. no) and text-based strategies (yes vs. no) of main idea selection and summarizing. They found that drawing was more effective than the text-based strategies in fostering comprehension of a scientific text about chemical structure and function of water molecules. However, because prior research has not focused on structural relations, more research is needed to test the effects of targeting different types of structural relations in drawing activities.

Second, to help students draw the targeted structural relations, instructional support should reduce irrelevant visual features and emphasize relevant structural relations. For instance, when students learn about the location of electrons (spatial relations), drawing activities should instruct students to draw each electron in relation to one another. However, when students learn about how electrons bond to form molecules (causal relations), drawing activities should provide the location of electrons and ask students to draw arrows to connect the electrons. Further, much prior research shows that instructional support should involve feedback on drawings to help students generate relevant visual cues and make inferences about concepts shown in their drawings (de Koning et al. 2010; diSessa 2004; Glogger-Frey et al. 2015). Students may lack the necessary knowledge to engage in bottom-up and top-down processes when they draw (Suwa et al. 2001; Uttal and O'Doherty 2008). Because they are novices learning the content, they may not know which features are relevant and how to relate them to one another. One example of such an instructional support system is CogSketch, a technology designed to assess visual and structural elements of students' drawings. Students label features as relevant concepts and CogSketch perceptually matches the labeled concepts in students' drawings to an instructor's drawing that contains the relevant features and structural relations (Forbus et al. 2011, 2017). Such novel technologies may help determine when students are not engaging productively with structural relations and provide feedback on how to use their drawings. Another way to help students focus on structural relations is to productively constrain how students draw by specifying what disciplinary drawing conventions to use (Prain and Tytler 2012). Research on mediated discourse suggests that drawing activities should focus students' attention on conventions of the given STEM discipline (Danish and Enyedy 2006). Some studies show that drawing activities that ask students to use conventions are more effective than drawing activities without guidance on which conventions to use (Forbus et al. 2017). If content is presented without conventions, students may generate ambiguous drawings, which are difficult for students to discuss with peers and for instructors to assess students' learning progress (Forbus et al. 2011, 2017). Therefore, to facilitate students' participation in STEM discourse, drawing activities should specify what conventions students should use to draw or help them determine which disciplinary conventions to use within their community (Danish and Enyedy 2006).

Third, prior research on mental model integration and mediated discourse suggests that drawing activities should ask students to generate multiple drawings. STEM professionals often generate multiple drawings rapidly and thus prior research on mediated discourse suggests providing more opportunities for students to draw and develop freehand or digital drawing skills (de Vere et al. 2011; Uziak and Fang 2017). With the advent of technologies such as CAD in engineering and modeling software in the sciences, some undergraduate curricula have further reduced the use of freehand drawing in their courses (Quillin and Thomas 2015; Uziak and Fang 2017). Without opportunities to practice drawing skills, students may not develop important skills that allow them to participate in their community as STEM professionals (Arcavi 2003; Frankel 2005; Johri et al. 2013; Ullman et al. 1990). Hence, much research suggests that instructors should design drawing activities to help students practice rapid and flexible drawing skills (de Vere et al. 2011) or ask them to generate multiple drawings (Cooper et al. 2017; Lehrer and Schauble 2003; Schank and Kozma 2002). One study showed that the number of drawings that students construct positively correlates with higher quality drawings and deeper understanding of content (Schank and Kozma 2002). Further, an experiment comparing different numbers of drawing prompts showed that drawing activities enhanced content knowledge and drawing quality, if prompts initially ask students to externalize their mental models followed by repeated prompts to revise their drawings and integrate new content into their mental models (Wu and Rau 2018). Hence, providing repeated drawing prompts may help students draw more frequently, revise their drawings to align with content, and thereby engage in the drawing practices of STEM professionals (Wu and Rau 2018; Prain and Tytler 2012).

In sum, drawing activities that focus on drawings should target specific structural relations and encourage students to generate multiple drawings. Instructional support should provide guidance on how students construct and use their drawings as well as opportunities for students to develop drawing skills.

Summary of Instructional Design Recommendations

Prior research has proposed instructional design recommendations that focus on different aspects of the drawing task. Specifically, they focus on engaging students with mental models, disciplinary discourse, and drawings. Recommendations that focus on *mental models* provide instructional support that helps students engage with content or reflect on their mental models. Recommendations that focus on *disciplinary discourse* provide instructional support that helps students engage with their learning community and use drawings as professionals do. Recommendations that focus on *drawings* provide instructional support that helps students use their drawings as a learning tool and focus on relevant structural relations. All recommendations aim to help students better engage with content through drawing activities and further engage students with their mental models, disciplinary discourse, or drawings.

At a broad level, our review of the recommendations shows some overlap in the *goals* of instructional designs for drawing activities. Specifically, most research proposes that drawing activities should (1) increase student engagement with relevant content through instructional design and (2) decrease or constrain irrelevant demands of the drawing task through instructional supports. First, to increase engagement with content, drawing activities should align with the targeted content and disciplinary practices. Further, they should help students externalize and manipulate the content in a visual-spatial form. This engagement with content helps students revise their mental models, learn how to use their drawings, and participate in the drawing practices of STEM professionals (Avgerinou and Pettersson 2011; Kirsh 2010; Palmer 1978; Pinker 1990). Second, because novice students may struggle to identify which features are relevant and how to use their drawings to engage with content, drawing activities should focus students on specific types of content, structural relations, or disciplinary practices by reducing extraneous features and constraining students' attention to specific aspects of the drawing task that are relevant for their given discipline and context. Instructional support can also help students identify relevant features and develop drawing skills through continuous feedback or explicit prompts to construct and reflect on drawings. Students may not use their drawings to clarify, organize, transform, or integrate the content without such support from peers, instructors, or educational technologies (Leenaars et al. 2013; Wilkerson-Jerde 2014).

Discussion

The goal of this article was to investigate how drawing activities help students learn STEM content. To this end, we reviewed prior research that has examined what learning processes effective drawing activities engage students in. We identified six distinct learning processes that have been studied in separate lines of work within the cognitive and sociocultural theoretical perspectives. Specifically, research from a cognitive perspective investigated how drawing activities engage students in (1) generative learning processes, (2) self-regulation processes, (3) mental model integration processes, and (4) spatial cognition processes. Research from a sociocultural perspective focused on (5) mediated discourse processes and (6) disciplinary practices processes. Each learning process enhances specific types of learning outcomes that match how students engage with the content. In Table 1, we summarize our review of the learning processes in relation to the theoretical perspectives they align with and which learning outcomes they enhance.

We describe each process separately because the processes have been investigated by separate lines of research and differ in terms of how they describe the nature and purpose of students' engagement. However, we propose that the processes are interrelated in a "stacked" manner which reflects how prior research on drawing activities has investigated learning processes at different levels of analysis. Particularly, processes from the cognitive perspective analyze specific elements of the drawing activity to isolate the processes that enhance learning outcomes, while the sociocultural perspective analyzes drawing activities as a complex system. We propose that the processes from sociocultural perspectives supervene those from the cognitive perspectives. Further, within each perspective, processes with specific learning goals supervene other processes with broader goals.

Because these processes have been examined separately, future research should verify whether the processes are related as proposed. Some work has begun to build theoretical frameworks that relate multiple learning processes. For instance, the CTDC from the cognitive perspective (Van Meter and Firetto 2013) has proposed that generative learning and self-regulation can be combined into a coherent theory in which self-regulation supervenes generative learning. Further, the RCA framework from the sociocultural perspective (Prain and Tytler 2012) proposes that disciplinary practices supervenes

Table 1 A summary of six learning processes underlying how drawing helps students learn STEM content, organized by line of research, learning processes, and learning outcomes

Theoretical perspective	Learning process	Learning outcomes
Cognitive	Generative learning (*Construct knowledge by translating content*)	• Learn visual-spatial STEM content • Enhance performance on higher-order and long-term assessments
Cognitive	Self-regulation (*Self-assess understanding of content to direct one's interaction with content*)	• Self-assess for what students least understand and self-regulate engagement with content
Cognitive	Mental model integration (*Activate mental models and revise them to align with content*)	• Increase self-assessment through externalizing mental models • Develop more sophisticated mental models
Cognitive	Spatial cognition (*Identify structural relations using top-down/bottom-up processes*)	• Learn structural relations in visual-spatial STEM content • Develop meta-representational competencies
Sociocultural	Mediated discourse (*Use disciplinary tools to represent and discuss content*)	• Adopt disciplinary conventions in drawings to participate in discourse with peers, instructors, or self • Increase proficiency in use of disciplinary conventions to engage with new content
Sociocultural	Disciplinary practices (*Transform content using drawings to solve problems or build knowledge in the discipline*)	• Shift in drawings from concrete to abstract (scientific modeling) or from abstract to concrete (design practices) • Develop adaptive drawing practices

mediated discourse. However, we were unable to find sociocultural studies that examine both mediated discourse and disciplinary practices due to differences in research populations and topics. Our framework of "stacked" learning processes is the first to define possible relationships across the theoretical perspectives.

In line with our framework, we found considerable overlap across learning processes in regard to the recommendations for instructional design of drawing activities. Hence, we organized the instructional design recommendations in Table 2 by how they engage students with the content through different aspects of the drawing activity: mental models, disciplinary discourse, or drawings. Across the recommendations, we found further overlap in recommendations, as exemplified by the middle category that engages students with drawings, which suggests that drawing activities may be designed to engage students in multiple processes at the same time. For instance, activities that prompt students to draw an atom to solve a disciplinary problem (disciplinary practices) may help students self-assess their understanding about the components of an atom (self-regulation), map structural relations about the location of electrons (spatial cognition), and abstract the structure of an atom in order to communicate about it with other community members (mediated discourse). To support these processes, instructors may provide supports that indicate what content to draw, prompt students to reflect on drawings during and after instruction, and provide peer interaction or instructor feedback on the drawings (Cooper et al. 2017; Wagner et al. 2017). The multiple types of support focus on different aspects of students' interaction with content such as how they process the content in relation to mental models, relate the content shown in drawings, and engage in disciplinary discourse about the content in their STEM community. Thus, drawing activities designed for multiple learning processes may serve complementary roles to help students learn STEM content.

Implications for Research

Our review reveals several opportunities for new lines of research. First, more work is needed to understand synergies among the different learning processes we identified. Some recent work has begun to combine multiple processes into coherent frameworks

Table 2 A summary of instructional design recommendations, organized by targeted learning outcomes focused on mental models, drawings, and disciplinary practices

To enhance…	Instructional design
Mental models	• Increase constructive engagement with content • Decrease cognitive load • Ask students to compare mental models to expert drawings • Provide prompts throughout or alongside content
Disciplinary discourse	• Support invention and revision process with individual and collaborative drawing phases • Focus students on the content and problem, not only the drawings
Drawings	• Targeted specific types of structural relations • Productively constrain drawing activities by reducing irrelevant cues, providing feedback, or specifying disciplinary conventions • Ask students to generate multiple drawings to practice and develop drawing skills

(Prain and Tytler 2012; Van Meter and Firetto 2013), but most prior research has focused on only one of the learning processes we described above. Consequently, we know little about whether and how drawing activities can be designed to engage students in multiple learning processes at the same time. Specifically, we need to investigate whether drawing activities that are designed to support one learning process may also support other learning processes, or whether different types of drawing activities are needed to optimally engage students in different learning processes. The drawing processes we identified may not be distinct, but a product of different lines of research examining similar processes. For instance, spatial cognition and mediated discourse both focus on the construction and meaning making of content shown in students' drawings but these processes have been investigated in separate lines of work from the cognitive and sociocultural perspectives, respectively. Future research should investigate how best to integrate multiple learning processes to focus not only on mental models, drawings, and disciplinary discourse but also to examine how these processes relate to one another.

Further, the development of drawing skills emerged as a focus across multiple lines of research. Hence, more research should investigate how various processes enhance one another in helping students develop drawing skills, such as meta-representational competencies. Prior research shows that students often fail to draw when appropriate for the given context and to engage with relevant content shown in their own drawings (Leenaars et al. 2013; Wilkerson-Jerde 2014). To address these issues, prior studies have reduced the demands of the drawing task through technology-based drag-and-drop interfaces to help students focus on relevant structural relations, rather than providing a blank page for students to draw all features (Schwamborn et al. 2011; Van Meter et al. 2006). However, research on spatial cognition and mediated discourse suggests that drawing skills may better help students learn content through the process and product of generating drawings (diSessa 2004). Such skills seem to support the work of STEM professionals who use drawings proficiently and thus may enhance students' ability to engage with their mental models and in disciplinary discourse. Additional research should investigate the role of drawing skills and how best to help students develop them through drawing activities in various learning environments to prepare students for future engagement with drawings.

Finally, more research should investigate how students develop drawing practices over time. Professionals differ significantly from novices in their ability to draw effectively to solve problems (Hay et al. 2013; Jee et al. 2014), yet it is unclear how STEM students develop these practices as they transition from novices to professionals (Johri et al. 2014; Prain and Tytler 2012). A longitudinal study could help us understand their trajectories and to what extent drawing practices develop by discipline. For example, it is unclear whether undergraduate students, who typically take courses in multiple disciplines, develop drawing practices that span across disciplines or are discipline-specific. While we typically consider discourse practices to be discipline-specific, our review shows that certain developmental trajectories appear in multiple disciplines (e.g., moving from concrete to abstract drawings). To date, prior research on the development of drawing practices has mainly focused on novices (e.g., primary school students in a math class) or professionals in one given discipline (e.g., mathematicians). Additionally, studies tend to be short-term interventions within a specific context, which are difficult to synthesize. Thus, more research is needed on students' trajectories from novices to professionals, especially among high-school and undergraduate students who prepare to pursue STEM careers (de Vere et al. 2011).

Implications for Instruction

Our review also identified several implications for instructors who design drawing activities. First, instructors should carefully target specific *learning processes* that map to specific *learning outcomes*. Each learning process differs in the specificity with which students engage with the drawing task and has consequences for how students engage with the content. For instance, if the goal is to help students understand the functional relations between the chambers of the heart from an animation, then drawing activities should engage students in spatial cognition in which students translate the animation into snapshots or scenes in a storyboard. To this end, drawing activities should help students identify the conceptually relevant features depicted in the animation (e.g., ask students to divide the animation into five scenes and write descriptions of functional relations for each scene) and provide scaffolds to help students draw the features for individual scenes (e.g., an empty comic strip with arrows connecting the five scenes or cutouts of different chambers of the heart for students to copy/paste). In order to help students enhance specific learning outcomes, the design of the drawing activity and level of support for this task should target the appropriate learning process.

Further, instructors should consider potential tradeoffs of drawing activities, in light of the targeted learning outcomes. Drawing activities can increase mental effort and may require higher-order assessments of complex knowledge to identify students' conceptual learning gains (Gadgil et al. 2012; Leutner and Schmeck 2014; Van Meter et al. 2006). Because drawing activities are difficult and time-consuming for students, drawing activities may not be appropriate unless they help students achieve specific targeted learning outcomes. An informal survey revealed that many undergraduate instructors do not consider why they include drawing activities, and particularly whether drawing activities serve as formative and summative assessment (Quillin and Thomas 2015). Formative drawing activities provide opportunities for students to receive feedback on their performance while they observe phenomena, relate visual features, and construct potential models. By contrast, summative drawing activities provide opportunities for students to reveal their mental model, record their observations, and communicate ideas clearly to others. If instructors use a type of summative drawing activity (e.g., an exam question that ask students to draw how certain molecules will bond), they should also design related types of formative drawing activities for students to practice drawing and receive feedback on the targeted content shown in drawings (e.g., practice problems in which they draw similar molecules and predict bonding behaviors).

Finally, instructors should consider drawing as a practice that students develop over time, rather than an intuitive skill or assessment method. The literature on drawing activities emphasizes that students require continuous feedback and opportunities to practice drawing (de Vere et al. 2011; diSessa and Sherin 2000; Valanides et al. 2013). For instance, drawing activities for mediated discourse suggest providing iterative cycles of inventing and revising drawings within their learning community to learn disciplinary conventions and practices. In comparison to reading, writing, and speaking, drawing is rarely taught in STEM learning environments (Anning 1999; Quillin and Thomas 2015). Studies show that STEM instructors often do not explain how and why they choose specific ways of drawing content and how they make visual-spatial inferences in their drawings, although they often explain how they engage with verbal STEM content (Anning 1999; Valanides et al. 2013). As a result, many students do not know how to draw effectively as a learning strategy. Because the practice of drawing develops over time, students should receive multiple opportunities to draw with continued guidance on what aspects of the content to draw (e.g., which structural relation), how to draw features (e.g., what disciplinary conventions to use), and how to engage with their drawings (e.g., when to reflect on drawings and revise them).

Limitations and Future Directions

Our review should be considered in light of the following limitations. First, we focused on the instructional design of drawing activities, not on the design of content-focused instructional materials. It is possible that content-focused materials can be tailored to better align with drawing activities. Because content-focused materials are typically designed to introduce students to disciplinary skills and practices, they may include complex and unintuitive conventions that students are not yet familiar with. Students may differ from professionals in how they engage with content and may therefore benefit from content-focused materials that are tailored to their developmental needs. Examining students' drawings as they change throughout the curriculum is one way to provide insight into how content should be presented to better align with drawing activities. Further, different types of content-focused materials may affect how students engage in drawing activities. For instance, prior work has shown mixed results for drawing activities on learning content from dynamic visualizations (Ploetzner and Fillisch 2017; Wagner et al. 2017), but these mixed results may stem from the features of the content or the visualizations and whether they complement the use of drawing activities. Hence, more research is needed to understand how the design of content-focused materials may interact with the design of drawing activities.

Second, we did not examine how differences between individual students affect how they engage with drawings. For instance, prior work shows that students' age can affect learning from drawing activities (Leutner and Schmeck 2014; Van Joolingen et al. 2015). One study asked children of ages 7–15 to create drawings in an informal environment without instructional support and found that older children created more accurate drawings, but were less motivated to draw (Van Joolingen et al. 2015). It is likely that factors such as prior knowledge, prior experience with drawing, and motivation will affect students' ability to engage with drawing. Hence, future research should examine the role of individual differences on drawing activities.

Third, we focused on how drawing activities enhance STEM content knowledge and thus did not discuss how drawing may enhance other outcomes such as creativity, laboratory skills, and motor processes. Further, we did not investigate other related processes such as embodied cognition, which primarily explores the role of the body, and distributed cognition, which primarily explores the role of drawing as an extension of the mind. Such processes and outcomes may also contribute to students' ability to learn STEM content knowledge and hence interact with the processes identified in this review. Thus, future work should investigate the research on broader processes and outcomes related to different types of drawing activities, and how these relate to the processes that enhance content knowledge.

Fourth, we briefly reviewed the role of the context when discussing sociocultural theories, but an investigation of how context affects students' learning from drawing was beyond the scope of this review. For example, prior research found that students engage with drawings differently when working individually versus collaboratively (Danish and Enyedy 2006). It is likely that even in controlled cognitive studies, factors in the context affected how students engage with content through drawing. Because drawing has not been at the focus of many instructional interventions, more research is needed to understand how to foster a classroom culture that promotes drawing as a learning strategy (de Vere et al. 2011). Such cultures may exist in certain educational contexts and are likely places where drawing activities are investigated, but a thorough investigation is needed to understand how drawing activities have been implemented and what role the context plays in different learning environments.

Fifth, in certain lines of research, we proposed instructional design recommendations based on evidence from only a few studies, due to the lack of prior research on these types of drawing activities. For instance, we suggested activating students' mental models and comparing them to an expert model in order to help students reflect on and revise their own mental models, based on one study (Gadgil et al. 2012). We believe this recommendation is likely valid because other observational and interview studies also suggest asking students to activate and compare mental models to content (Valanides et al. 2013; Vosniadou 1994). However, more work is needed, particularly in the new lines of research (e.g., self-regulation), to provide evidence for the instructional design recommendations of drawing activities.

Finally, as mentioned, our review suggests that the six learning processes we identified may not be distinct, but rather synergistic processes that have been investigated in different lines of research. For instance, both generative learning and mental model integration involve integrating content with mental models. However, prior work on generative learning has not focused on confronting flawed mental models and work on mental model integration has not focused on cognitive activity. Alternatively, it is possible that these two processes are distinct in nature, which may explain the differences we found in learning outcomes (see Table 1). Future work should investigate how the learning processes from separate lines of research intersect and diverge. Such research would yield insights into how drawing activities may combine instructional designs to enhance different learning processes that yield complementary learning outcomes.

Conclusion

Our review reveals how drawing activities can help students learn STEM content. We show that drawing activities facilitate six distinct learning processes that enhance students' engagement with content. We synthesized prior research on these learning processes in a framework to show how they build upon one another to facilitate different levels of engagement with content. The drawing activities are effective if implemented with instructional support that targets specific goals of the drawing task. The findings yield insights for instructors and researchers on how best to design drawing activities that help students engage with STEM content.

Our findings expand prior work by showing that focusing on *learning processes* can reveal how students benefit from drawing activities. Prior work on the effectiveness of drawing activities has not connected the instructional design of drawing activities to learning processes and learning outcomes. Moreover, it has not investigated how learning processes overlap across different drawing activities. Therefore, we recommend that future work should explicitly consider what learning process(es) drawing activities foster. Such work will further provide theoretical insights into the effects of drawing activities and empirical evidence that connect instructional design and learning outcomes.

Our review is timely for the educational psychology community. Over the past years, research on drawing activities has been increasing (Ainsworth et al. 2011; Tippett 2016), but separate lines of research have focused on different learning processes and outcomes. Our review paves the road toward a synthesis across these lines of research, which will help us better understand when, how, and why drawing activities are effective (or ineffective) for students' learning. Given that drawing activities play a major role in helping both STEM professionals and students construct knowledge in STEM to advance the field, we anticipate that such research will have significant impact on educational practices. Helping students use drawing as a learning strategy will help prepare them not only to make sense of content but also to participate in disciplinary practices for thinking, problem-solving, and communicating in the STEM fields.

Acknowledgements This research was supported by the Wisconsin Center for Education Research, the National Science Foundation through Award #DUE1611782, and the Institute of Education Sciences, U.S. Department of Education through Award #R305B150003 to the University of Wisconsin-Madison. The opinions expressed are those of the authors and do not represent views of the National Science Foundation or the U.S. Department of Education.

References

Acevedo Nistal, A., Van Dooren, W., & Verschaffel, L. (2012). What counts as a flexible representational choice? An evaluation of students' representational choices to solve linear function problems. *Instructional Science, 40*(6), 999–1019. https://doi.org/10.1007/s11251-011-9199-9.

Ainsworth, S. E., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science (New York, N.Y.)*, *333*(August), 1096–1097. https://doi.org/10.1126/science.1204153.

Ainsworth, S. E., Stieff, M., Desutter, D., Tytler, R., Prain, V., Panagiotopoulos, D., … Puntambekar, S. (2016). Exploring the value of drawing in learning and assessment. Proceedings of international conference of the learning sciences, ICLS, 2, 1082–1089.

Anning, A. (1999). Learning to draw and drawing to learn. *International Journal of Art Design Education, 18*(2), 163–172. https://doi.org/10.1111/1468-5949.00170.

Arcavi, A. (2003). The role of visual representations in the learning of mathematics. *Educational Studies in Mathematics, 52*(3), 215–241.

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: a comparison of students and expert practitioners. *Journal of Engineering Education, 96*(4), 359–379. https://doi.org/10.1002/j.2168-9830.2007.tb00945.x.

Avgerinou, M. D., & Pettersson, R. (2011). Toward a cohesive theory of visual literacy. *Journal of Visual Literacy, 30*(2), 1–19. https://doi.org/10.1080/23796529.2011.11674687.

Backhouse, M., Fitzpatrick, M., Hutchinson, J., Thandi, C. S., & Keenan, I. D. (2017). Improvements in anatomy knowledge when utilizing a novel cyclical "observe-reflect-draw-edit-repeat" learning process. *Anatomical Sciences Education, 10*(1), 7–22. https://doi.org/10.1002/ase.1616.

Berland, L., & Crucet, K. (2015). Epistemological trade-offs: accounting for context when evaluating epistemological sophistication of student engagement in scientific practices. *Science Education*, *0*(0), 1–25. https://doi.org/10.1002/sce.21196.

Bobek, E., & Tversky, B. (2014). Creating visual explanations improves learning. In *Proceedings of the 36th annual conference of the cognitive science society* (pp. 206–211). Austin: Cognitive Science Society.

Brew, A., Fava, M., & Kantrowitz. (2012). Drawing connections: New directions in drawing. *Tracey: Drawing and Visualisation Research*, *Drawing Kn*(September), 0–17.

Brooks, M. (2009). Drawing, visualisation and young children's exploration of "big ideas.". *International Journal of Science Education, 31*(February 2015), 319–341. https://doi.org/10.1080/09500690802595771.

Chang, H.-Y. Y., Quintana, C., & Krajcik, J. (2014). Using drawing technology to assess students' visualizations of chemical reaction processes. *Journal of Science Education and Technology, 23*(3), 355–369. https://doi.org/10.1007/s10956-013-9468-2.

Cheng, M., & Gilbert, J. K. (2009). Towards a better utilization of diagrams in research into the use of representative levels in chemical education. In J. K. Gilbert & D. Treagust (Eds.), *Multiple representations in chemical education* (Vol. 4, pp. 55–73). https://doi.org/10.1007/978-1-4020-8872-8_4.

Chi, M. T. H. (2008). Three types of conceptual change: belief revision, mental model transformation, and categorical shift. In S. Vosniadou (Ed.), *Handbook of research on conceptual change* (pp. 61–82). Hillsdale: Erlbaum.

Chi, M. T. H., & Wylie, R. (2014). The ICAP framework: linking cognitive engagement to active learning outcomes. *Educational Psychologist, 49*(4), 219–243. https://doi.org/10.1080/00461520.2014.965823.

Cooper, M. M., Grove, N., Underwood, S. M., & Klymkowsky, M. W. (2010). Lost in Lewis structures: An investigation of student difficulties in developing representational competence. *Journal of Chemical Education, 87*(8), 869–874. https://doi.org/10.1021/ed900004y.

Cooper, M. M., Corley, L. M., & Underwood, S. M. (2013). An investigation of college chemistry students' understanding of structure-property relationships. *Journal of Research in Science Teaching, 50*(6), 699–721. https://doi.org/10.1002/tea.21093.

Cooper, M. M., Stieff, M., & DeSutter, D. (2017). Sketching the invisible to predict the visible: from drawing to modeling in chemistry. *Topics in Cognitive Science*, 1–19. https://doi.org/10.1111/tops.12285.

Cox, R. (1999). Representation construction, externalised cognition and individual differences. *Learning and Instruction, 9*(4), 343–363. https://doi.org/10.1016/S0959-4752(98)00051-6.

Cromley, J. G., Bergey, B. W., Fitzhugh, S., Newcombe, N., Wills, T. W., Shipley, T. F., & Tanaka, J. C. (2013). Effects of three diagram instruction methods on transfer of diagram comprehension skills: the critical role of inference while learning. *Learning and Instruction, 26*, 45–58. https://doi.org/10.1016/j.learninstruc.2013.01.003.

Danish, J. A., & Enyedy, N. (2006). Unpacking the mediation of invented representations. In *7th International Conference on Learning Sciences (ICLS '06)* (pp. 113–119). International Society of the Learning Sciences.

Danish, J. A., & Saleh, A. (2014). Examining how activity shapes students' interactions while creating representations in early elementary science. *International Journal of Science Education, 36*(14), 2314–2334. https://doi.org/10.1080/09500693.2014.923127.

Davatzes, A., Gagnier, K., Resnick, I., & Shipley, T. F. (2018). Learning to form accurate mental models. *Eos*, (February), 1–10. https://doi.org/10.1029/2018EO091643.

Day, S. B., & Goldstone, R. L. (2012). The import of knowledge export: connecting findings and theories of transfer of learning. *Educational Psychologist, 47*(3), 153–176. https://doi.org/10.1080/00461520.2012.696438.

De Bock, D., Verschaffel, L., Janssens, D., Van Dooren, W., & Claes, K. (2003). Do realistic contexts and graphical representations always have a beneficial impact on student's performance? Negative evidence from a study on modelling non-linear geometry problems. *Learning and Instruction, 13*(4), 441–463. https://doi.org/10.1016/S0959-4752(02)00040-3.

de Koning, B. B., Tabbers, H. K., Rikers, R. M. J. P., & Paas, F. (2010). Learning by generating vs. receiving instructional explanations: two approaches to enhance attention cueing in animations. *Computers and Education*. https://doi.org/10.1016/j.compedu.2010.02.027.

de Vere, I., Melles, G., & Kapoor, A. (2011). Developing a drawing culture: new directions in engineering education. Proceedings of the 18th international conference on engineering design (ICED 11): Impacting society through engineering design, Vol 8: Design education, 8(august), 226–235.

de Vries, E. (2006). Students' construction of external representations in design-based learning situations. *Learning and Instruction, 16*(3), 213–227. https://doi.org/10.1016/j.learninstruc.2006.03.006.

diSessa, A. A. (2004). Metarepresentation: native competence and targets for instruction. *Cognition and Instruction, 22*(3), 293–331. https://doi.org/10.1207/s1532690xci2203_2.

diSessa, A. A., & Sherin, B. L. (2000). Meta-representation: an introduction. *The Journal of Mathematical Behavior, 19*(4), 385–398.

diSessa, A. A., Hammer, D., Sherin, B. L., & Kolpakowski, T. (1991). Inventing graphing: meta-representational expertise in children. *The Journal of Mathematical Behavior, 10*, 117–160.

Duit, R., & Treagust, D. F. (2008). Conceptual change: a discussion of theoretical, methodological and practical challenges for science education. *Cultural Studies of Science Education, 3*(2), 297–328. DOI. https://doi.org/10.1007/s11422-008-9090-4.

Enyedy, N. (2005). Inventing mapping: creating cultural forms to solve collective problems. *Cognition and Instruction, 23*(4), 427–466. https://doi.org/10.1207/s1532690xci2304_1.

Evagorou, M., Erduran, S., & Mäntylä, T. (2015). The role of visual representations in scientific practices: from conceptual understanding and knowledge generation to 'seeing' how science works. *International Journal of STEM Education, 2*(1), 11. https://doi.org/10.1186/s40594-015-0024-x.

Fan, J. E. (2015). Drawing to learn: how producing graphical representations enhances scientific thinking. *Translational Issues in Psychological Science, 1*(2), 170–181. https://doi.org/10.1037/tps0000037.

Fiorella, L., & Mayer, R. E. (2015). Eight ways to promote generative learning. *Educational Psychology Review*, 1–25. https://doi.org/10.1007/s10648-015-9348-9.

Fiorella, L., & Zhang, Q. (2018). Drawing boundary conditions for learning by drawing. *Educational Psychology Review*, pp. 1–23. Educational Psychology review. https://doi.org/10.1007/s10648-018-9444-8.

Fish, J., & Scrivener, S. (2007). Amplifying the mind's eye: sketching and visual cognition. *Leonardo, 23*(1), 117–126.

Forbus, K. D., Usher, J., Lovett, A., Lockwood, K., & Wetzel, J. (2011). CogSketch: sketch understanding for cognitive science research and for education. *Topics in Cognitive Science, 3*(4), 648–666. https://doi.org/10.1111/j.1756-8765.2011.01149.x.

Forbus, K. D., Chang, M., McLure, M., & Usher, M. (2017). The cognitive science of sketch worksheets. *Topics in Cognitive Science*, 1–22. https://doi.org/10.1111/tops.12262.

Frankel, F. (2005). Translating science into pictures: a powerful learning tool. *Invention and Impact: Building Excellence in Undergraduate Science, Technology, Engineering, and Mathematics (STEM) Education*, 155–158.

Gadgil, S., Nokes-Malach, T. J., & Chi, M. T. H. (2012). Effectiveness of holistic mental model confrontation in driving conceptual change. *Learning and Instruction, 22*(1), 47–61. https://doi.org/10.1016/j.learninstruc.2011.06.002.

Gagnier, K. M., Atit, K., Ormand, C. J., & Shipley, T. F. (2016). Comprehending diagrams: sketching to support spatial reasoning. *Topics in Cognitive Science*, 1–19. https://doi.org/10.1111/tops.12233.

Gan, Y. (2007). Drawing out ideas: student-generated drawings' roles in supporting understanding of "light". *Institute for Knowledge Innovation and Technology Summer Institute Summer Institute, 2007, IKIT, Ontario Institute for Studies in Education, University of Toronto*, (1995), 1–36.

Gentner, D., & Markman, A. B. (1997). Structure mapping in analogy and similarity. *American Psychologist, 52*(1), 45–56. https://doi.org/10.1037/0003-066X.52.1.45.

Glogger-Frey, I., Fleischer, C., Grüny, L., Kappich, J., & Renkl, A. (2015). Inventing a solution and studying a worked solution prepare differently for learning from direct instruction. *Learning and Instruction, 39*, 72–87. https://doi.org/10.1016/j.learninstruc.2015.05.001.

Gobert, J. D. (2018). The effects of different learning tasks on model-building in plate tectonics: Diagramming versus explaining. *Journal of Geoscience Education, 53*(4):444–455

Gobert, J. D., & Clement, J. J. (1999). Effects of student-generated diagrams versus student-generated summaries on conceptual understanding of causal and dynamic knowledge in plate tectonics. *Journal of Research in Science Teaching, 36*(1), 39–53. https://doi.org/10.1002/(SICI)1098-2736(199901)36:1<39::AID-TEA4>3.0.CO;2-I.

Goldschmidt, G. (1994). On visual design thinking: the vis kids of architecture. *Design Studies, 15*(2), 158–174. https://doi.org/10.1016/0142-694X(94)90022-1.

Goldschmidt, G. (2003). The backtalk of self-generated sketches. *Design Issues, 19*(1), 72–88. https://doi.org/10.1162/074793603762667728.

Goldschmidt, G. (2014). An anthology of theories and models of design. https://doi.org/10.1007/978-1-4471-6338-1.

Greenhalgh, T., & Peacock, R. (2005). Effectiveness and efficiency of search methods in systematic reviews of complex evidence: audit of primary sources. *British Medical Journal, 331*(7524), 1064–1065. https://doi.org/10.1136/bmj.38636.593461.68.

Greeno, J. G., & Hall, R. P. (1997). Practicing representation: Learning with and about representational forms. *The Phi Delta Kappan, 78*(5), 361–67. https://doi.org/10.2307/20405797

Harle, M., & Towns, M. H. (2013). Students' understanding of primary and secondary protein structure: drawing secondary protein structure reveals student understanding better than simple recognition of structures. *Biochemistry and Molecular Biology Education, 41*(6), 369–376. https://doi.org/10.1002/bmb.20719.

Hay, D. B., Williams, D., Stahl, D., & Wingate, R. J. (2013). Using drawings of the brain cell to exhibit expertise in neuroscience: exploring the boundaries of experimental culture. *Science Education, 97*(3), 468–491. https://doi.org/10.1002/sce.21055.

Hegarty, M. (2004). Mechanical reasoning by mental simulation. *Trends in Cognitive Sciences, 8*(6), 280–285. https://doi.org/10.1016/j.tics.2004.04.001.

Hegarty, M. (2012). Meta-representational competence as an aspect of spatial intelligence. *Cognitive Science*, 1240–1241.

Hellenbrand, J. (2018). Lernen durch sinnstiftendes Zeichnen. Universität Duisburg-Essen.

Jee, B. D., Gentner, D., Uttal, D. H., Sageman, B., Forbus, K. D., Manduca, C. a., et al. (2014). Drawing on experience: how domain knowledge is reflected in sketches of scientific structures and processes. *Research in Science Education, 44*(6), 859–883. https://doi.org/10.1007/s11165-014-9405-2.

Johri, A., Roth, W.-M., & Olds, B. M. (2013). The role of representations in engineering practices: taking a turn towards inscriptions. *Journal of Engineering Education, 102*(1), 2–19. https://doi.org/10.1002/jee.20005.

Johri, A., Olds, B. M., & O'Connor, K. (2014). Situative frameworks for engineering learning research. *Cambridge Handbook of Engineering Education Research*, (January 2014), 47–66. https://doi.org/10.1017/CBO9781139013451.006.

Jonassen, D. H. (2003). Using cognitive tools to represent problems. *Journal of Research on Technology in Education, 35*(3), 362–381. https://doi.org/10.1080/15391523.2003.10782391.

Jonassen, D. H., Strobel, J., & Gottdenker, J. (2005). Model building for conceptual change. *Interactive Learning Environments, 13*(1), 15–37. https://doi.org/10.1080/10494820500173292.

Kavakli, M., & Gero, J. S. (2001). Sketching as mental imagery processing. *Design Studies, 22*(4), 347–364. https://doi.org/10.1016/S0142-694X(01)00002-3.

Kavakli, M., & Gero, J. S. (2002). The structure of concurrent cognitive actions: A case study on novice and expert designers. *Design Studies, 23*(1), 25–40.

Kirsh, D. (2010). Thinking with external representations. *AI & Society, 25*(4), 441–454. https://doi.org/10.1007/s00146-010-0272-8.

Kothiyal, A., Murthy, S., & Chandrasekharan, S. (2016). "Hearts pump and hearts beat": engineering estimation as a form of model-based reasoning. Proceedings of international conference of the learning sciences, ICLS, 1(2015), 242–249.

Kozma, R., & Russell, J. (2005). Students becoming chemists: developing representational competence. *Visualization in Science Education*, 121–145.

Kozma, R., Chin, E., Russell, J., & Marx, N. (2000). The roles of representations and tools in the chemistry laboratory and their implications for chemistry learning. *Journal of the Learning Sciences, 9*(February 2013), 105–143. https://doi.org/10.1207/s15327809jls0902_1.

Lajoie, S. P. (2008). Metacognition, self regulation, and self-regulated learning: a rose by any other name? *Educational Psychology Review, 20*(4), 469–475. https://doi.org/10.1007/s10648-008-9088-1.

Latour, B. (1986). Visualization and cognition. *Knowledge and Society*. https://doi.org/10.1002/9780470979587.ch9.

Latour, B. (1990). Drawing things together. In *Representations in scientific practice* (pp. 19–68). Cambridge: MIT Press. https://doi.org/10.1166/jnn.20.

Leenaars, F. A. J., Van Joolingen, W. R., & Bollen, L. (2013). Using self-made drawings to support modelling in science education. *British Journal of Educational Technology, 44*(1), 82–94. https://doi.org/10.1111/j.1467-8535.2011.01272.x.

Lehrer, R., & Schauble, L. (2003). Symbolic communication in mathematics and science: co-constituting inscription and thought. In *Language, Literacy, and Cognitive Development: The Development and Consequences of Symbolic Communication* (pp. 167–192).

Lehrer, R., & Schauble, L. (2015). The development of scientific thinking. Handbook of Child Psychology and Developmental Science, 671–714. https://doi.org/10.1002/9781118963418.childpsy216.

Leopold, C., & Leutner, D. (2012). Science text comprehension: drawing, main idea selection, and summarizing as learning strategies. *Learning and Instruction, 22*(1), 16–26. https://doi.org/10.1016/j.learninstruc.2011.05.005.

Leopold, C., & Leutner, D. (2015). Improving students' science text comprehension through metacognitive self-regulation when applying learning strategies. *Metacognition and Learning, 10*(3), 313–346. https://doi.org/10.1007/s11409-014-9130-2.

Leutner, D., & Schmeck, A. (2014). The generative drawing principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 433–448). New York: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.022.

Leutner, D., Leopold, C., & Sumfleth, E. (2009). Cognitive load and science text comprehension: effects of drawing and mentally imagining text content. *Computers in Human Behavior, 25*(2), 284–289. https://doi.org/10.1016/j.chb.2008.12.010.

Lin, L., Ha Lee, C., Kalyuga, S., Wang, Y., Guan, S., & Wu, H. (2016). The effect of learner-generated drawing and imagination in comprehending a science text. *The Journal of Experimental Education, 0973*(March). https://doi.org/10.1080/00220973.2016.1143796.

Lobato, J., Hohensee, C., & Diamond, J. M. (2014). What can we learn by comparing students' diagram-construction processes with the mathematical conceptions inferred from their explanations with completed diagrams? *Mathematics Education Research Journal, 26*(3), 607–634. https://doi.org/10.1007/s13394-013-0106-3.

Mason, L., Lowe, R., & Tornatora, M. C. (2013). Self-generated drawings for supporting comprehension of a complex animation. *Contemporary Educational Psychology, 38*(3), 211–224. https://doi.org/10.1016/j.cedpsych.2013.04.001.

Mayer, R. E. (2009). Research-based principles for designing multimedia instruction. In *Applying Science of Learning in Education* (pp. 1–12). Retrieved Feb 6 2016 http://hilt.harvard.edu/files/hilt/files/background_reading.pdf.

McCracken, W. M., & Newstetter, W. C. (2001). Text to diagram to symbol: Representational transformations in problem-solving. *Frontiers in Education Conference, 2001. 31st Annual*, *2*, F2G–13–17. https://doi.org/10.1109/FIE.2001.963721.

Nathan, M. J., & Alibali, M. W. (2010). Learning sciences. *Wiley Interdisciplinary Reviews: Cognitive Science, 1*(3), 329–345. https://doi.org/10.1002/wcs.54.

Nathan, M. J., & Sawyer, R. K. (2014). Foundations of the learning sciences. In *The Cambridge Handbook of Learning Sciences* (pp. 21–43).

Nathan, M. J., Eilam, B., & Kim, S. (2007). To disagree, we must also agree: how intersubjectivity structures and perpetuates discourse in a mathematics classroom. *Journal of the Learning Sciences, 16*(4), 523–563. https://doi.org/10.1080/10508400701525238.

National Research Council. (2012a). *A framework for K-12 science education: practices, crosscutting concepts, and Core ideas*. Washington, D.C.: National Academies Press. https://doi.org/10.17226/13165.

National Research Council. (2012b). Discipline-based education research: understanding and improving learning in undergraduate science and engineering. *Journal of Engineering Education, 102*(4), 261. https://doi.org/10.1002/jee.20030.

Nersessian, N. J. (2008). Mental modeling in conceptual change. Handbook of Research on Conceptual Change, (April), 768. https://doi.org/10.4324/9780203154472.ch21.

Nichols, K., Ranasinghe, M., & Hanan, J. (2013). Translating between representations in a social context: a study of undergraduate science students' representational fluency. *Instructional Science, 41*(4), 699–728. https://doi.org/10.1007/s11251-012-9253-2.

Nyachwaya, J. M., Mohamed, A.-R., Roehrig, G. H., Wood, N. B., Kern, A. L., & Schneider, J. L. (2011). The development of an open-ended drawing tool: an alternative diagnostic tool for assessing students' understanding of the particulate nature of matter. *Chemistry Education Research and Practice, 12*(2), 121–132. https://doi.org/10.1039/c1rp90017j.

Nyachwaya, J. M., Warfa, A.-R. M., Roehrig, G. H., & Schneider, J. L. (2014). College chemistry students' use of memorized algorithms in chemical reactions. *Chemistry Education Research and Practice, 15*(1), 81–93. https://doi.org/10.1039/c3rp00114h.

Osborne, R. J., & Wittrock, M. C. (1983). Learning science: a generative process. *Science Education, 67*(4), 489–508. https://doi.org/10.1002/sce.3730670406.

Palmer, S. E. (1978). Fundamental aspects of cognitive representation. In *Cognition and Categorization* (pp. 259–303).

Papaphotis, G., & Tsaparlis, G. (2008). Conceptual versus algorithmic learning in high school chemistry: the case of basic quantum chemical concepts. Part 1. Statistical analysis of a quantitative study. *Chemistry Education Research and Practice, 9*(4), 323. https://doi.org/10.1039/b818468m.

Parnafes, O. (2010). Representational practices in the activity of student-generated representations (SGR) for promoting conceptual understanding. Proceedings of the 2010 international conference of the learning sciences, 1(July), 301–308.

Parnafes, O., Aderet-German, T., & Ward, E. T. (2012). Drawing for understanding: an instructional approach for promoting learning and understanding. *Paper Presented at the Annual Meeting of the American Educational Research Association, Vancouver, Canada*, (February), 1–36.

Pinker, S. (1990). A theory of graph comprehension. In *Artificial Intelligence and the Future of Testing* (pp. 73–126). https://doi.org/10.1145/2046684.2046699.

Ploetzner, R., & Fillisch, B. (2017). Not the silver bullet: learner-generated drawings make it difficult to understand broader spatiotemporal structures in complex animations. *Learning and Instruction, 47*, 13–24. https://doi.org/10.1016/j.learninstruc.2016.10.002.

Prain, V., & Tytler, R. (2012). Learning through constructing representations in science: a framework of representational construction affordances. *International Journal of Science Education, 34*(17), 2751–2773. https://doi.org/10.1080/09500693.2011.626462.

Purcell, A. T., & Gero, J. S. (1998). Drawings and the design process. *Design Studies, 19*(4), 389–430. https://doi.org/10.1016/S0142-694X(98)00015-5.

Quillin, K., & Thomas, S. (2015). Drawing-to-learn: a framework for using drawings to promote model-based reasoning in biology. *CBE Life Sciences Education, 14*(1), 1–16. https://doi.org/10.1187/cbe.14-08-0128.

Roth, W.-M., & McGinn, M. K. (1998). Inscriptions: toward a theory of representing as social practice. *Review of Educational Research, 68*(1), 35–59. https://doi.org/10.3102/00346543068001035.

Rau, M. A. (2017). Conditions for the effectiveness of multiple visual representations in enhancing STEM learning. *Educational Psychology Review, 29*(4):717–61. https://doi.org/10.1007/s10648-016-9365-3.

Sawyer, R. (2005). *Social emergence: Societies as complex systems*. New York, NY: Cambridge University Press.
Schank, P., & Kozma, R. B. (2002). Learning chemistry through the use of a representation based knowledge building environment. *Journal of Computers in Mathematics and Science Teaching, 21*(3), 253–279.
Scheiter, K., Schleinschok, K., & Ainsworth, S. E. (2017a). Why sketching may aid learning from science texts: contrasting sketching with written explanations. *Topics in Cognitive Science*, 1–17. https://doi.org/10.1111/tops.12261.
Scheiter, K., Schubert, C., & Schüler, A. (2017b). Self-regulated learning from illustrated text: eye movement modelling to support use and regulation of cognitive processes during learning from multimedia. *British Journal of Educational Psychology*, 1–15. https://doi.org/10.1111/bjep.12175.
Schleinschok, K., Eitel, A., & Scheiter, K. (2017). Do drawing tasks improve monitoring and control during learning from text? *Learning and Instruction*, 1–16. https://doi.org/10.1016/j.learninstruc.2017.02.002.
Schmeck, A., Mayer, R. E., Opfermann, M., Pfeiffer, V., & Leutner, D. (2014). Drawing pictures during learning from scientific text: testing the generative drawing effect and the prognostic drawing effect. *Contemporary Educational Psychology, 39*(4), 275–286. https://doi.org/10.1016/j.cedpsych.2014.07.003.
Schmidgall, S. P., Eitel, A., & Scheiter, K. (2018). Why do learners who draw perform well? Investigating the role of visualization, generation and externalization in learner-generated drawing. *Learning and Instruction*, (January). https://doi.org/10.1016/j.learninstruc.2018.01.006.
Schnotz, W. (2002). Commentary: towards an integrated view of learning from text and visual displays. *Educational Psychology Review, 14*(1), 101–120. https://doi.org/10.1023/A:1013136727916.
Schnotz, W. (2005). An integrated model of text and picture compherension. In *The Cambridge handbook of multimedia learning* (pp. 49–69).
Schnotz, W. (2014). Integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *The Cambridge handbook of multimedia learning* (pp. 72–103). Cambridge: Cambridge University Press. https://doi.org/10.1017/CBO9781139547369.006.
Schraw, G., Crippen, K. J., & Hartley, K. (2006). Promoting self-regulation in science education: Metacognition as part of a broader perspective on learning. *Research in Science Education, 36*(1–2), 111–139. https://doi.org/10.1007/s11165-005-3917-8.
Schwamborn, A., Thillmann, H., Opfermann, M., & Leutner, D. (2011). Cognitive load and instructionally supported learning with provided and learner-generated visualizations. *Computers in Human Behavior, 27*(1), 89–93. https://doi.org/10.1016/j.chb.2010.05.028.
Schwartz, D. L., & Heiser, J. (2006). Spatial representations and imagery in learning. The Cambridge Handbook of the Learning Sciences, 283–298. https://doi.org/10.1017/CBO9780511816833.
Schwartz, D. L., & Martin, T. (1988). Inventing to prepare for future learning: the hidden efficiency of encouraging original student production in statistics instruction. *Cognition and Instruction, 22*(2), 129–184. https://doi.org/10.1207/s1532690xci2202_1.
Schwarz, C. V., Reiser, B. J., Davis, E. a., Kenyon, L., Achér, A., Fortus, D., et al. (2009). Developing a learning progression for scientific modeling: making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632–654. https://doi.org/10.1002/tea.20311.
Sins, P. H. M., Savelsbergh, E. R., & van Joolingen, W. R. (2005). The difficult process of scientific modelling: an analysis of novices' reasoning during computer-based modelling. *International Journal of Science Education, 27*(14), 1695–1721. https://doi.org/10.1080/09500690500206408.
Snyder, J. (2013). Drawing practices in image-enabled collaboration. In *Proceedings of the 2013 conference on computer supported cooperative work* (pp. 741–751). ACM.
Stieff, M., Hegarty, M., & Deslongchamps, G. (2011). Identifying representational competence with multi-representational displays. *Cognition and Instruction, 29*(1), 123–145. https://doi.org/10.1080/07370008.2010.507318.
Suwa, M., Tversky, B., Gero, J., & Purcell, T. (2001). Seeing into sketches: regrouping parts encourages new interpretations. Visual and Spatial Reasoning in Design II, (1994), 207–219.
Sweller, J. (2010). Element interactivity and intrinsic, extraneous, and germane cognitive load. *Educational Psychology Review, 22*(2), 123–138. https://doi.org/10.1007/s10648-010-9128-5.
Tippett, C. D. (2016). What recent research on diagrams suggests about learning with rather than learning from visual representations in science. *International Journal of Science Education, 38*(5), 725–746. https://doi.org/10.1080/09500693.2016.1158435.
Tversky, B. (2011). Visualizing thought. *Topics in Cognitive Science, 3*(3), 499–535. https://doi.org/10.1111/j.1756-8765.2010.01113.x.
Ullman, D. G., Wood, S., & Craig, D. (1990). The importance of drawing in the mechanical design process. *Computers and Graphics, 14*(2), 263–274. https://doi.org/10.1016/0097-8493(90)90037-X.
Uttal, D. H., & O'Doherty, K. (2008). Comprehending and learning from visual representations: a developmental approach. In *Visualization: Theory and Practice in Science Education* (pp. 53–72). Springer Netherlands.

Uziak, J., & Fang, N. (2017). Improving students ' freehand sketching skills in mechanical engineering curriculum. *International Journal of Mechanical Engineering Education*, *0*(0), 1–13. https://doi.org/10.1177/0306419017744156.

Valanides, N., Efthymiou, I., & Angeli, C. (2013). Interplay of internal and external representations: students' drawings and textual explanations about shadow phenomena. *Journal of Visual Literacy, 32*(2), 67–84.

Van Joolingen, W. R., Aukes, A. V. A., Gijlers, H., & Bollen, L. (2015). Understanding elementary astronomy by making drawing-based models. *Journal of Science Education and Technology, 24*(2–3), 256–264. https://doi.org/10.1007/s10956-014-9540-6.

Van Meter, P. (2001). Drawing construction as a strategy for learning from text. *Journal of Educational Psychology, 93*(1), 129–140. https://doi.org/10.1037/0022-0663.93.1.129.

Van Meter, P., & Firetto, C. M. (2013). Cognitive model of drawing construction. In *Learning Through Visual Displays* (pp. 247–280).

Van Meter, P., & Garner, J. (2005). The promise and practice of learner-generated drawing: literature review and synthesis. *Educational Psychology Review, 17*(4), 285–325. https://doi.org/10.1007/s10648-005-8136-3.

Van Meter, P., Aleksic, M., Schwartz, A., & Garner, J. (2006). Learner-generated drawing as a strategy for learning from content area text. *Contemporary Educational Psychology, 31*(2), 142–166. https://doi.org/10.1016/j.cedpsych.2005.04.001.

Verstijnen, I. M., van Leeuwen, C., Goldschmidt, G., Hamel, R., & Hennessey, J. M. (1998). Creative discovery in imagery and perception: combining is relatively easy, restructuring takes a sketch. *Acta Psychologica, 99*(2), 177–200. https://doi.org/10.1016/S0001-6918(98)00010-9.

Vosniadou, S. (1994). Capturing and modeling the process of conceptual change. *Learning and Instruction, 4*(1), 45–69. https://doi.org/10.1016/0959-4752(94)90018-3.

Vosniadou, S. (2003). Exploring the relationships between conceptual change and intentional learning. In G. M. Sinatra & P. R. Pintrich (Eds.), *Intentional conceptual change* (pp. 377–406). Mahwah: Lawrence Erlbaum Associates, Inc.. https://doi.org/10.1177/1350507604048274.

Vosniadou, S., & Brewer, W. F. (1992). Mental models of the earth: a study of conceptual change in childhood. *Cognitive Psychology, 24*(4), 535–585. https://doi.org/10.1016/0010-0285(92)90018-W.

Wagner, I., Schnotz, W., Stieff, M., & Mayer, R. E. (2017). Learning from dynamic visualization. In R. K. Lowe & R. Ploetzner (Eds.), *Learning from dynamic visualization—innovations in research and application* (pp. 333–356). Berlin: Springer. https://doi.org/10.1007/978-3-319-56204-9.

Wang, C. Y., & Barrow, L. H. (2011). Characteristics and levels of sophistication: an analysis of chemistry students' ability to think with mental models. *Research in Science Education, 41*(4), 561–586. https://doi.org/10.1007/s11165-010-9180-7.

White, T., & Pea, R. (2011). Distributed by design: on the promises and pitfalls of collaborative learning with multiple representations. *The Journal of the Learning Sciences, 20*(530), 489–547. https://doi.org/10.1080/10508406.2010.542700.

Wilkerson-Jerde, M. H. (2014). Construction, categorization, and consensus: Student generated computational artifacts as a context for disciplinary reflection. *Educational Technology Research and Development, 62*(1), 99–121. https://doi.org/10.1007/s11423-013-9327-0.

Wilkerson-Jerde, M. H., Gravel, B. E., & Macrander, C. A. (2015). Exploring shifts in middle school learners' modeling activity while generating drawings, animations, and computational simulations of molecular diffusion. *Journal of Science Education and Technology, 24*(2–3), 396–415. https://doi.org/10.1007/s10956-014-9497-5.

Winne, P. H., & Hadwin, A. F. (1998). Studying as self-regulated learning. *Metacognition in Educational Theory and Practice*, 277–304. https://doi.org/10.1016/j.chb.2007.09.009.

Wylie, R., & Chi, M. T. H. (2014). The self-explanation principle in multimedia learning. In R. E. Mayer (Ed.), *The Cambridge Handbook of Multimedia Learning* (pp. 413–432). Cambridge University Press. https://doi.org/10.1016/0364-0213(89)90002-5.

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.

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.

Yang, M. C. (2009). Observations on concept generation and sketching in engineering design. *Research in Engineering Design, 20*(1), 1–11. https://doi.org/10.1007/s00163-008-0055-0.

Zhang, Z. H., & Linn, M. C. (2011). Can generating representations enhance learning with dynamic visualizations? *Journal of Research in Science Teaching, 48*(10), 1177–1198. https://doi.org/10.1002/tea.20443.