Despite mixed results in research on student learning from drawing in science, there is growing interest in the potential for this visual mode, in tandem with other modes, to enact and enable student reasoning in this subject. Building on current research in this field, and using a micro-ethnographic approach informed by socio-semiotic perspectives, we aimed to identify how and why student drawing can contribute to student reasoning and learning. In our study, secondary school students were challenged to explore and collaboratively create explanatory representations of phenomena including through drawing. Data were generated using multiple wall- and ceiling-mounted cameras capable of continuously tracking groups of students negotiating these representational challenges. Our analysis proceeded through active and iterative viewing of the extensive video record, and the identification of themes to establish possible relationships between drawing and reasoning. Through this process, we (a) identify multiple necessary conditions and varied opportunities for student drawing to enact and enable reasoning, and (b) extend current understandings of how the particular affordances of this mode interact with these conditions to contribute to student learning in science.

**KEYWORDS**

drawing, inquiry science, learning in science, multimodal representations, reasoning, semiotics
1 | INTRODUCTION

As part of the growing interest in representational work and multimodal reasoning in science classrooms, there is increasing focus on understanding how student drawing contributes to learning. Currently in its infancy, this research is yet to generate authoritative claims about the value of this sign-making for reasoning in science. In this study, we were guided by (a) sociocultural perspectives on reasoning as the use of cultural symbolic tools to analyze and solve problems and make claims (Vygotsky, 1981), and (b) Peirce’s (1998a, 1998b, 1998c) pragmatist view of meaning making, or semiosis, as the ongoing processes whereby meaning makers generate, consolidate, and share meanings through making links between signs, objects, and their application in real-world contexts. We therefore view our approach to drawing in science as socio-semiotic. A recent review of relevant literature (Ainsworth, Prain, & Tytler, 2011) incorporated this perspective and more traditional cognitivist approaches to identify five reasons for the value of drawing in science as a classroom activity, including: (a) to enhance engagement, (b) learn how to represent meanings in science, (c) engage in reasoning in science, (d) learn scientific concepts and processes, and (e) communicate claims. While recognizing that drawing enables different kinds of learning across these five dimensions, in this paper, we focus in particular on drawing to reason, and how in this role it can underpin learning in science. We use evidence from a micro-ethnographic analysis of activity before, during, and after student drawing to generate new insights into the reasoning and learning possibilities of drawing.

1.1 | Studies of learning through drawing in science

Drawing has a long history within studies of students’ conceptions as part of interviews exploring aspects of students’ spatial and visual thinking (Osborne, Black, Meadows, & Smith, 1993; Sherin, Krakowski, & Lee, 2012; Vosniadou, 2002) or as part of class journals revealing coordination of ideas (Shepardson & Britsch, 2001). Our own interest, however, is in drawing as a constructive reasoning and learning process. Recent reviews concerning drawing to learn (e.g., Van Meter & Firetto, 2013; Waldrip & Prain, 2012) reported that there are few studies that investigate the efficacy of drawing activities in science classrooms, and these have varied results.

Increasing recognition of the centrality of visualization as both process and product in coming to know in science (Gilbert, 2005) has provided impetus to explore the role of visual and spatial modalities. Drawing is one such visual modality, and researchers have positioned it as a potential key resource for reasoning and learning in science classrooms. Schwartz (1995) noted the benefits of collaborative drawing, in which the specificity and explicitness of drawings provide opportunities for peers to exchange and clarify ideas. Collaboratively constructed drawings conceived of as visualization tools have been shown to support the development of cosmological literacy (Buck Bracey, 2017). Gijlers, Weinberger, van Dijk, Bollen, and van Joelingen (2013) explored the conditions under which computer-based collaborative drawing worked to establish shared representation and deeper science understandings. The public sharing of representations allows students to critique the clarity, coherence, and content of drawings and attendant ideas (Linn, Lewis, Tsuchida, & Songer, 2000).

Other studies (Stieff, 2011; Zhang & Linn, 2011) have shown marginal learning gains from coupling drawing with dynamic visualizations of complex molecular structures in high school chemistry. Similarly, Stieff and deSutter (2016) found only marginal learning gains when students made observational, then reflective sketches of a dynamic simulation of molecular behavior. Zhang and Linn
(2013) demonstrated that generation of drawings associated with a dynamic chemical simulation led to enhanced learning compared with selection of alternative images from the visualization, but no advantage compared with complex selection of ideas that led students to replay the simulation. They argue that such a complex selection can encourage students to consider ideas that may otherwise go unexamined, and that a combination of drawing and such a selection may be advantageous for learning.

Studies of drawing have identified different purposes for this sign-making. It is used to: translate text into an image (Brooks, 2009; Leopold & Leutner, 2012; Hackling & Prain, 2005), rerepresent computer simulations (Stieff & deSutter, 2016), record dissections (Panagiotopoulos, Ainsworth, & Peter Wigmore, 2016), interpret processes (Hubber, Tytler, & Haslam, 2010), and enact speculative accounts of unfamiliar or abstract phenomena (Ainsworth et al., 2011; Prain & Tytler, 2012). In this study, we seek to investigate more closely, through micro-ethnographic analyses, ways of reasoning through drawing suggested in previous research (Ainsworth, 2006; Kirsh, 2010; Tytler, Prain, Hubber, & Haslam, 2013). In particular, we consider drawing as potentially a process that enables students to generate proto-models that may be to varying degrees emergent, nonformal, partial, or unresolved. In constructing and assessing drawings, students need to consider how their drawing corresponds to features of the subject they are representing, and also to consider the extent to which it is coherent both within component parts of the drawing and across related representations. These interlocking requirements of correspondence and coherence are key features of model-based reasoning central to the epistemic practices of science (Lehrer & Schauble, 2006a).

If previous studies variously conceptualize and position drawing as (a) an instrument that serves other processes, such as clarifying mental models or communicating findings, or (b) a mode of sign-making that enacts new understandings, then perhaps this explains the lack of uniform findings about learning with or from drawing (Van Meter & Garner, 2005). Van Meter, Aleksic, Schwartz, and Garner (2006) argue that drawing supports learning when students need to translate between linguistic and visual modes, thus enriching understanding. They argue that coordination of detail across modes results in “a mental model of the concept that is more flexible than isolated representations can afford” (Van Meter & Garner, 2005, p. 322).

From our own socio-semiotic perspective, with its roots in Peirce (1998a, 1998b, 1998d), we claim in principle that drawing, as a generative sign-making process, like all other forms of semiosis, has the potential to enable sign-makers to invest, consolidate, extract, test, inspect, and revise intended, unintended, and emergent meanings, thus potentially enacting reasoning processes. This is not to argue that this form of sign-making in itself, and independent of other meaning-making modes, does all the cognitive work, but rather that drawing has the potential to enact or to prompt and support student conceptual clarification and model-based reasoning.

1.2 The relation between reasoning and learning

From a Peirce (1992) perspective, reasoning is a response to doubt through establishing justified belief. An “unceasing process of ongoing semiosis” (Smith, 2005, p. 192) provides the means to settle belief, and “all reasoning is an interpretation of signs of some kind” (Peirce, 1998a, p. 4). In this way, understandings are constructed and shared as representational forms, where we continually cycle around/through the interplay of signs, objects in context, and new and confirmed meanings from these interactions (Peirce, 1998b), with each interplay necessarily leading to another (ad infinitum) to define the unfolding of meaning-making processes.
This reasoning is not just deliberate conscious problem-solving, but rather as Peirce (1998e) argues there is often no sharp line of demarcation between reasoning and perceiving. While reasoning is a logical process, it can also have a distinctly intuitive character. We reason often without conscious awareness of this process as we perceptually engage with phenomena; this is often the beginning of what may become an extended meaning-making process that leads to reasoning of a more explicit nature. In this way, from a socio-semiotic perspective, reasoning is necessarily a multi-modal process of meaning making—we can reason by doing as much as by thinking. This is most evident with the abductive form of reasoning, what Peirce (1998c) considers to be the driver of new meanings as it generates the hypotheses that deduction (general to specific) and induction (specific to general) go to work on.

The contemporary Peircian scholar Magnani (2013) makes a case for the value of drawing from a semiotic (and pragmatic) perspective. He argues for drawings as “epistemic mediators” (Magnani, 2013, p. 303), which can constitute a form of abductive reasoning when they afford idea generation. Using evidence from disciplinary discovery practices, Magnani proposes that drawings can serve a mirror role: representing speculative thoughts in an external form that can then be manipulated to not only consolidate but also develop ideas. They can also serve an unveiling role: opening up new “gateways to imaginary entities” (Magnani, 2013, p. 318); new ideas, not previously considered. Drawing is acknowledged as both a visual reasoning process and a means for subsequent reasoning processes.

Drawing, from these perspectives, mediates student meaning making, and is part of the multi-modal, cultural construction of knowledge in the classroom (Vygotsky, 1981). By making use of both Vygotsky and Peirce, a social/cultural and semiotic account of drawing becomes possible, which enables a potentially more comprehensive understanding of this meaning-making process than just adopting one of these approaches.

1.3 Drawing as a constructive activity within a guided inquiry pedagogy

In a program of research spanning 10 years, on guided inquiry approaches to science learning, drawing has been used as one mode among others by students to construct representations as claims in response to structured challenges involving experimental exploration with material resources (Prain, Tytler, & Peterson, 2009; Tytler et al., 2013). In theorizing this approach, we have drawn on studies of the epistemic practices of science itself that foreground the active role of representational work in scientific discovery (Gooding, 2004, 2006; Latour, 1986), and the increasingly pervasive role of diverse representational work in generating and communicating knowledge more generally (Elkins, 2011).

These ideas align with Lemke’s (Lemke, 1990; Lemke, 2004) research to identify the crucial role of representational work in science classrooms, as students are introduced to the complex multimodal conventions that underpin explanatory work in the discipline. Moje (2007) has characterized representational work as central to the development of scientific disciplinary literacy, through which students come to know and achieve competence in the discursive practices that characterize science. Cognitive research has investigated the role of different representational modes and how these might best be coordinated to support conceptual learning (Ainsworth, 2006, 2008).

Our own work sits within a strand of research that focuses mainly on student generation of representations, rather than interpretation of authorized ones, though in practice, students are also interpreters of their own signs. Researchers in this tradition argue that students benefit from multiple opportunities to explore, elaborate, and rerepresent ongoing understandings in and through a variety
of representations, and stress the importance of students and teachers negotiating realized meanings in these processes across modes (Ford & Forman, 2006; Greeno & Hall, 1997; Lehrer & Schauble, 2006a, 2006b; Tytler, Peterson, & Prain, 2006; Waldrip, Prain, & Carolan, 2010). Different forms of representational work support different, and necessarily partial, understandings of phenomena, and students need to access and acknowledge the advantages and limitations of a variety of representations in reasoning about phenomena (including data generation, speculative thinking and interpretation, and scoping investigations) (Cox, 1999; Greeno & Hall, 1997).

In theorizing our approach (Prain & Tytler, 2012), we developed a model of representation construction affordances to explain how students’ creation of their own representations supports learning in that this process aligns with how scientists explore, generate, refine, and share claims. We recognize that this process entails both scientists and students accessing, coordinating and integrating multiple, multimodal representations, where drawing is one mode. We argued that all representational modes have particular affordances (Gibson, 1979; Norman, 1999) that act as productive constraints on thinking. We proposed that drawing has multiple affordances in that this sign-making process demands visual and spatial specificity within a limited space, focuses attention on spatial relations between parts of the drawing, forces attention on detail in the case of life drawing, or on specificity of visual and spatial relations in the case of speculative drawings such as particle representations of macro phenomena. This account aligns with Van Meter et al.’s (2005) findings concerning the advantage of drawing from text, where students moved back and forth between descriptive text, illustration, and further information, to refine their own drawings which demand specificity through their spatial constraint. We further note that drawing potentially affords a productive integrative way for students to address two requirements in persuasive scientific claim-making and modeling. In science, these requirements are that a drawing should (a) show a correspondence between explanatory drawing features and key features of the phenomena, and (b) demonstrate internal coherence as an explanatory account. Research where drawing supports model-based reasoning is evident in our own and other research, such as the extensive research by Lehrer and Schauble and colleagues (Lehrer & Schauble, 2012; Lehrer, Schauble, Carpenter, & Penner, 2000), but this research has to date not sought to identify in more detail the affordances of this mode.

In summary, in the current literature in this field, there is acceptance of the key role of visualization in doing and learning science, there are theoretical socio-semiotic warrants for understanding drawing as meaning-making and reasoning, and there is a growing general case for the particular affordances of drawing as one mode among several to enable and enact reasoning. In our study, we sought to investigate in further detail these leads about the relationship between drawing and reasoning.

Our study entails data generation in guided inquiry classrooms in which students are challenged to construct multiple representations in response to conceptual challenges. While drawing was not the only focus of the research, many of the constructed representations were drawings. The data generation, which involves comprehensive video and audio capture of pairs of students collaboratively reasoning in response to the challenges, allows us to examine the role of drawing in enacting collaborative reasoning about science phenomena. The paper will address the following research questions:

1. What processes of reasoning and learning can drawing enact and support in inquiry science?
2. What are the conditions under which drawing enacts reasoning and learning processes?
3. In what ways can drawing enact reasoned interactions in science classrooms?
2 METHODS

2.1 Data generation

Six single sessions were conducted in a specially designed “Science of Learning” classroom with 10 wall and ceiling mounted video cameras with zoom and tilt capacity, and radio microphones on each desk, controlled from a room with visual access to the classroom (via a one-way mirror). Year 7 classes (students aged 12 years old) were bussed into the classroom and were taught by their own science teacher for single 1-hr lessons. They explored the topics of levers, flower classification, toys and energy, and astronomy. Some sessions were run twice (including toys and energy) allowing adjustments to improve the learning focus, while other sessions were undertaken only once (flower classification and astronomy). On each occasion, different students were involved.

The session plans were consistent with the school’s Year 7 curriculum, and were developed in collaboration with the participating teachers to reflect the representation construction (guided inquiry) approach. So, while the sessions were carefully scripted, they were designed to afford opportunities for student discovery through collaboration with peers and the teacher. These were stand-alone sessions only tangentially related to topic sequences at the school. The main aim of the research was to investigate the ways in which collaborating pairs of students coordinated talk, gesture, experimental exploration, and multiple representations to reason about science phenomena. In each of the lessons, drawing was an important feature, either using pen and paper, or markers on a small whiteboard.

The sophisticated video/audio setup permitted the capturing of almost everything that was taking place, thus partiality was not an issue when it came to the collection of data. Rather, partiality was a key concern in regard to deciding what data to analyze. However, while the positioning of cameras, microphones, resources, students, and teachers was carefully planned by the researchers and video/audio technicians to maximize the collection of rich and relevant data, decisions still needed to be made on the fly to address any developing concerns (e.g., shifting microphones, zooming cameras in/out, and students/teachers moving to clear the line of sight of the cameras).

The structure of each session was broadly similar. First, the teacher reminded students of work done earlier in the year in that topic, and outlined the main ideas to be explored in the session. These were as far as possible aligned to concepts students had covered in previous work. The challenge tasks were then introduced. In each case, the drawing challenge linked to other modes—experimental work (exploring balance conditions on a model see-saw; investigating reproductive systems of flowers and creating a dichotomous key; investigating how small mechanical toys work), 3D modeling (working with Earth models and torches to construct explanations of astronomical observations), talk, and gesture. Within the set tasks, students were free in each case to interpret them in a variety of ways. This is a core feature of a “representational challenge”; that it is open and has more than one solution. In each session, there was an initial challenge that was to an extent “introductory”, followed by brief class discussion, then a second, more “open task” which students tackled through investigation, drawing, and in some cases construction of a digital account using iPads. Some pairs of students were also asked to present their ideas to another pair on the same table and come to a shared view. In some cases, the drawings were done in pen on paper, but on other occasions whiteboards and markers were used to provide flexibility in modifying the drawings.

The drawings and other student representational work in such inquiry tasks are always approximations to standard textbook representational forms, which themselves must be considered as incomplete and approximate in the sense that there are inevitably variations in ways of perceiving and interpreting phenomena. In representation-focused guided inquiry approaches (Hubber et al., 2010), variation in student representations becomes highly valued by the teacher who can use them with
students to establish productive ways forward to construct representations consistent with scientific perspectives (Lehrer & Schauble, 2012; Tytler et al., 2013). In this particular case, because we were dealing with single lessons only loosely connected to the school curriculum, albeit taught by the classroom teacher, there was limited opportunity to follow up student work beyond a brief reporting back period with some teacher comment.

2.2 | Analysis

The methodology was micro-ethnographic (Erickson, 2006) in that video/audio records and student produced artifacts were analyzed in detail to explore the way groups of students generated understandings through coordinating talk, gesture, writing, and visual representation construction. Reasoning and learning were tracked through the groups’ work on the tasks, as the students grappled with the challenge and discussed and negotiated solutions using representations across a variety of modes.

The multiple cameras and microphones meant that 10 video tracks of about 50 min were generated for each class, with a camera focused on each of six tables able to separately capture a video and audio record of two pairs of students. One camera tracked the teacher, who had a separate radio microphone. Thus, in all, the data available for this analysis consists of a continuous video/audio record of 12 × 6 = 72 groups for 1 hr, plus a record of the teacher over that time. Two ceiling mounted cameras were also employed to provide a separate view of students drawing from above, which proved very useful in capturing the progress of drawings coordinated with student talk and gesture, and manipulation of equipment or models.

With such a rich and extensive data set, selection became a significant methodological issue that defined our analysis (Ferguson, Aranda, Tytler, & Gorur, 2019 for a detailed discussion of our approach), which was both iterative and dialogic. Videos of each group, and student-produced artifacts, were viewed and discussed over an extended period by the team. This was done in conjunction with an ongoing engagement with literature, theories, theorists, and later transcripts. Two researchers led this exploration of the data, each focusing on three different filmed sessions. These experiences were shared at regular team meetings. In this way, we immersed ourselves in this rich and extensive field—what we call “video as a field”—much as an ethnographer would do in a physical field (through extended presence in a classroom). Through this process of familiarization (or, indeed, immersion), six pairs were selected for particular analysis (half of the total) for each session, where the dialogue and actions were clear and illustrative of learning, and students were mainly on task. Transcripts were made of these students' discussions and actions.

We then viewed these segments to identify the way the different representational modes of material manipulation, talk and gesture, exploration of 3D models, and particularly drawing were contributing to learning through this inquiry process. Viewing/reviewing of the video established that the drawing process functioned differently in the generation of meaning for different tasks, and within tasks across different groups. This variation occurred despite our initial intention to situate drawing within each task in a broadly similar way. To clarify the way drawing interacted with other modes within the inquiry process, a preliminary narrative of each task was constructed around the theme of drawing and its purposes and contribution to reasoning, amounting to a broad categorization of the way drawing interacted with other modes in different topics and task structures. Further discussion among the team, and re/viewing of videos, established a set of emergent principles regarding the different roles that drawing played in these tasks in relation to other modes, its specific affordances and challenges. In some tasks, such as toy investigation for instance, the major reasoning work fell to material exploration, gesture, and oral speculation. We identified in the drawings themselves
variation in the mix between symbolic and iconic features, and the different positioning of interpretive mechanism through the drawing. This ranged for instance from identifying reproductive structures in flowers aligned with a classic model, to interpreting spatial relations in a model Earth–Sun system that explained astronomy phenomena, to constructing a dichotomous key to structure flower observations. The variation across groups in how the drawing served reasoning purposes was also documented to establish the conditions leading to this variation, including interpretation of tasks, the role of prior knowledge, and the way students positioned the drawing as either generative of ideas, or more narrowly descriptive.

In this process, as we identified the variation across tasks and across groups, particular examples indicative of these variations in the role of drawing emerged for us as especially significant within the variety of drawing instances. These examples were not representative in the traditional sense of providing the basis for making general/universal claims about student meaning-making as drawing. Rather, we followed Massumi (2002) and MacLure (2010) in considering these examples as yielding rich insights into contexts where drawing appeared to support or be superfluous to learning. These were instances/moments capable of productively disrupting our preconceptions about the generative potential of drawing.

Where occasional disagreements occurred among the research team as to the examples and their meaning and how to pursue the analysis, these were resolved through a constant returning to the video field. The examples that eventually emerged (more numerous than the set that are presented in this paper for reasons of space) were those moments/instances that came to resonate with the research team as a whole, as exemplars of the distinctive operation of drawing in different topics, with different task structures. The collaborative and material-discursive nature of this research process led to a coalescing of ideas around/through these purposefully selected examples.

The examples emerging from this iterative and dialogic process led to further searching and refinement of ideas and deeper engagement with the data. In this way, the set of emergent principles regarding the operation of different task conditions, the interaction of drawing with other modes, and variation in group engagement with reasoning were further examined and coalesced into two major themes concerning the fundamental ways in which drawing functioned as a reasoning process for learning. Each of these themes was evident in multiple examples, a selection of which is presented in the paper. While the paper is structured around these themes, the examples are used to also illuminate the task conditions under which drawing serves reasoning.

3 | FINDINGS AND ANALYSIS

Through an iterative process of micro-ethnographic analysis of students' use of drawings in responding to the inquiry challenges, we identified two key themes relating to the ways in which drawing enacts collaborative or individual reasoning. These themes relate to our research questions thus:

1. *Reasoning occurs both “through” and “from” drawing within a multimodal inquiry process (RQ1&2):* In the tasks, drawing to a varying extent constituted a reasoning process. In drawing, students make visuo-spatial claims as part of reasoning across modes, with its particular affordance seen as productive constraint on reasoning through its visual and spatial specificity (Prain & Tytler, 2012). The extent to which drawing enacted reasoning varied across tasks, depending on the positioning of drawing in relation to other modal aspects of the task, how
students viewed the purpose of drawing, and the conceptual/representational resources they brought to the task.

2. **Drawing can enact collaborative reasoning and monitoring (RQ3):** Drawing, through opening visuo-spatial aspects of meaning-making to inspection, can entail corepresentation and collaborative reasoning with peers, or the teacher, and for students to monitor their own meaning making.

These two themes were often interconnected through the particular challenge tasks students undertook, such that they cannot be associated exclusively with distinct events. In the following, each of these themes will be illustrated and further articulated through analysis of one or more examples of student interactions and productions.

### 3.1 Theme 1: Drawing as reasoning within a multimodal inquiry process

It became clear, exploring the multiple roles for drawing across all tasks and groups, that the process of drawing played two essentially different roles. In many cases, drawing functioned as a *generative* reasoning process in that students were actively involved, through drawing, in advancing, negotiating, and refining visuo-spatial claims. In some of the examples described in the following, students construct explanations or problem-solving through orchestrating ideas across multimodal representations, including drawing, verbalizing, annotating, and linking with material models or artifacts. In other examples, students consider the purpose of drawing as primarily *communicative*, for instance where it was a relatively straightforward copy of a flower, or representation of a toy car mechanism that had been resolved through material investigation prior to the drawing task. Nevertheless, we argue that even in these cases, drawing can enact reasoning to some degree. The examples we have selected illustrate this spectrum of possibilities.

#### 3.1.1 Example 1.1: Toy mechanisms

A topic that illustrates a range of aspects of reasoning involved students being asked to generate representations of the energy pathways of small toys (wind up cars, balloon cars, or mousetrap cars, walking or flipping toys, a ball emitting light when bounced, and an elastic band model plane) and then to construct a drawing to show the mechanisms by which it worked. For these toys, some of the energy and machine concepts were quite sophisticated and the toy mechanisms sufficiently hidden for students to struggle in generating ideas through their drawings. In explaining the mechanisms for many of these toys, physically manipulating the toys themselves together with verbal speculative discussion was more generative of ideas than the drawings that tended to be cast by students as communicative in function and which were often superficial in nature.

However, we describe below an example that illustrates the generative nature of drawing in enacting reasoning, even where its purpose seemed to be construed by students as passive recording/communicating.

In this example, two boys were working with a toy car powered by a mousetrap spring mechanism, and the act of drawing the car involved close attention on the exposed mechanism. The subsequent drawing is shown in Figure 1, together with an explanation of energy changes. The boy doing the drawing (BS2) moved back and forth between the car itself and the drawing, with his partner (BS1) actively contributing ideas about aspects of the mechanism as BS2 renders and annotates them. In this process, gesture played an important part in aligning their understandings of the correspondence relations between the model and the drawing.
BS1: Well ... we need to think about how it works actually how it did work. So I'm thinking that what we should do ... first draw a diagram of the actual toy.

BS2: Yeah as in if we do side on then we can draw the mechanics of the actual thing.

BS1: Yeah.

BS2: So we've got wheels ... and ... axis going through it. (BS1 displays the toy while BS2 draws it).

BS1: And then ...-

BS2: Then we have ... Now that coming down to the second wheel at the back.

BS1: And they're all the same angles and the same size as well, and it's ... two wheels (BS2 is carefully drawing).

They begin to consider the spring mechanism using material manipulation and gesture to explore and focus attention:

BS1: There's a spring.
BS2: There's a spring in the middle and the thing (Talking over each other) coming around (BS2 checks the toy carefully and focuses back on the drawing), and at the back here ... and there's a rope attached to here so when you pull the ... (Talking over each other) pull it back-

BS1: So what happens now that, the science is ... when you pull the lever back, the further you pull it the more energy it's gathering, and the more energy it's sustaining.

They continue talking about the energy exchange and then refer again to the mechanism. This time, however, BS2 reasons about the mechanism through the drawing itself.

BS1: And the wheel should theoretically turn forward, but that did not occur.
BS2: Except it didn't occur with .... So we got that, then we pull it back to here (referring now exclusively to the drawing, pointing out the elements of the mechanism) and
the rope should be wrapping around the axle at the back, except our ... the blu-tak doesn't work very well for us.

From this point on the students annotate the drawing, referring to the details in the drawing to discuss the mechanism. Every now and then, they refer back to the car itself. In this case, the drawing performed a proto-modeling function of focusing attention on details of the working of the toy, involving the establishment of correspondence between the drawing and the phenomenon and coherence in selecting key elements of the car mechanism and organizing and revising relations between these.

3.1.2 | Example 1.2: Flower classification

In the flower classification task, students were shown a canonical generic representation of the reproductive structures of a flower, and reminded of the reproductive processes of flowering plants. They were then given flowers with a wide variety of structures to dissect, draw, and annotate. The drawings, in pen on paper, provided an important function in guiding students’ observation and identification of reproductive features. Figure 2 shows an example of the clearer, more competent drawings. Here, we again point out the nature of drawing as a claim-making process, specifically a process of proto-modeling, involving students carefully cutting the flowers, identifying through observation and discussion the alignment of flower structures with a projected canonical diagram, then selecting salient features and spatially arranging these in an annotated diagram. This drawing process enables complex model-based reasoning entailing both correspondence and coherence. This involves careful observation of the component parts of the real flower (selection and abstraction) and their correspondence with the canonical model, as well as understanding the role of different structures (coherence requirement). The drawing process involves students in this case moving between the flower itself and the canonical drawing displayed on the board showing the characteristic reproductive structures, and aligning these with the very different arrangements in the real flowers they were exploring. From this perspective, Figure 2 is the product of drawing as a reasoning process in which correspondence is generated (and checked) between the annotated drawing artifacts, the canonical representation of flower structure, and the structures of

FIGURE 2  Annotated drawings of a variety of flower reproductive structures
the flower itself. This process also entails understanding the coherence of the abstracted model represented in the canonical version, and the identification of this model in the specimen.

Figure 3 illustrates the process of executing the left-hand drawing. The student decides, on a suggestion from an adjacent pair, to count the petal layers and their arrangement on the flower. She does so first using a magnifier, then teasing apart the layers to count them, holding, and orienting the flower to record the petal details. In drawing the “ovule with embryo sac,” she teases apart the flower to expose its inner structures, draws them, then engages in a process of looking back and forward between the flower and the canonical diagram projected on the classroom whiteboard, consulting with her partner and other pair before deciding a structure is the “stame” (sic). The process of drawing thus stimulated close observation of flower structures and selection and arrangement of particular aspects, and annotation through comparison with the canonical diagram.

It transpired that students had little prior exposure to flower reproductive structures, and many found it difficult to link the classic (and canonical) reproductive drawing to what they were observing, constructing drawings that lacked the precision or detail of Figure 2. In these cases, again, without the knowledge and other resources needed to generate reasonable claims, drawing performed a predominantly communicative role with minimal generation of the fresh ideas we associate with reasoning. In this example, there are attempts at correspondence without sufficient knowledge or support to understand or meet coherence requirements.

From these examples, we argue that the drawing process can entail model-based reasoning, involving proto-modeling to establish correspondence and coherence claims. These claims can entail: the selection and abstraction of key features of phenomena (flower drawings), the orchestration and refinement of their relations (mousetrap car), focusing on and structuring observation and experimentation (flower drawings and mousetrap car), and integrating emerging understandings (annotated flower drawings). This reasoning through drawing inevitably involves multimodal orchestration across visuo-spatial, verbal and written, gestural, and material modes.

3.2 | Theme 2: Drawing to support monitoring and collaborative reasoning

The astronomy tasks provided evidence of the productively constraining nature of the 2D drawing to focus attention on key visual and spatial features of Earth–Sun relations. In the astronomy session,
students were reminded that understanding astronomical events required the coordination of two views—a space view, and an Earth-centered view—and to illustrate this were shown images of the Earth in space, and images taken from Earth. They were given two challenges, the first introductory task asked for a drawing that describes to a 7-year-old boy how it can be evening in Melbourne and morning in London at the same time. After this task, each group was given a second task varying in difficulty and matched, on the teacher's advice, to students' capabilities. Pairs were required for this task to draw an explanatory diagram on their whiteboard. Each group was given a small Earth globe and torch to help them work out what was happening.

In these tasks, drawing acted as a common ground through which groups of students revealed their ideas, reasoned collaboratively, and negotiated agreement about the visuo-spatial or other aspects of the astronomical phenomena under investigation. Through rendering visuo-spatial reasoning inspectable, the drawing process involved corepresentation as pairs of students created, negotiated and refined their characterizations, and individuals monitored and modified their visuo-spatial and associated claims. This reasoning process was evident in two closely related respects: (a) in the initial drawing process through an orchestration of talk, observation, model manipulation, and gesture accompanying decisions as students made their inscriptions; and (b) in the evaluation and negotiation of modifications to the drawings, made possible by the ongoing inspectability of the drawings. This occurred for individuals, as they reevaluated their work (as with the mousetrap car), and for groups. It occurred also with teachers, for whom the drawing made visible specific aspects of student thinking. In this research, because the teachers were not required to shape student learning to the extent they normally would, this monitoring was not a primary focus. However, there were many examples in the video record of teacher interventions built around the students' drawings.

### 3.2.1 | Example 2.1: The angle of the Sun in different seasons

This example features a pair of students constructing a whiteboard drawing to respond to the challenge “show why the Sun is higher in Australia in summer than winter.” We draw attention here to the constant revising of the drawing as the pair struggled to visualize the spatial and temporal

![FIGURE 4 Checking geometric relations in the drawing using a torch and globe [Color figure can be viewed at wileyonlinelibrary.com]](image-url)
relations that would help them make sense of the seasonal variation in the angle of the Sun. The boys quickly began drawing once they received instructions. The transcript below shows how their reasoning involved coordination between the drawing and the 3D Earth model (globe). The drawing again functioned as proto-modeling, requiring the students to establish correspondence between the 2D representation and the 3D model to tease out a convincing coherent account within and across these models in which the necessity of the change in angle could be understood.

Figure 4 shows the students checking their ideas using the 3D model, as they work on the drawing.

<table>
<thead>
<tr>
<th>1</th>
<th>BS1: This is the Earth… The Sun, in the middle of the solar system. BS2: Oh now I get it. BS1: I get it too. BS1: Okay? Earth's on a tilt-</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>BS1: Hang on. Did I put the tilt the wrong way? BS1: Did I put the tilt the wrong way? Is it that way? BS2: I'm pretty sure it's that way. Yeah. BS1: No but it goes anti-clockwise so it'll be like this. So yeah, it's this way, okay. I get it.</td>
</tr>
<tr>
<td>3</td>
<td>BS1: … OK. I know how to explain, I'm just trying to make it as accurate as I can.</td>
</tr>
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</table>

Episode 1 demonstrates that the constant monitoring/self-checking BS1 engages in as he continually erases and redraws, expressing his developing insight through the drawing process (“Oh now I get it”). In Episode 2, when he doubts his translation into 2D (“Did I put the tilt the wrong way?”), he goes back to the 3D model, gesturally indicating corresponding features, and then progressively updates his drawing. BS2 in this sequence is a bystander to BS1’s reasoning and drawing journey, but nonetheless remains engaged in the reasoning.

They then continue somewhat falteringly, with frequent discussion and erasing, to draw the Earth’s orbit and tilt with the Earth in summer and winter positions. This challenge can be understood as needing to identify correspondences between (in this case) the exploratory drawing and the 3D model as the basis for explaining the seasonal sunlight variation effects deriving from the Earth’s orbit and tilt (a claim again based on coherence within and across these partial models).

In Episodes 4 and 5, a collaborative phase of the boys’ drawing and reasoning is shown, with BS2 achieving insight (“Oh yeah, now I got it”), and in Episode 5, he takes over an aspect of the drawing/annotation when BS1 seems to falter. He uses the drawing, and a pen along with gesturing, to articulate his insight to BS1 (“When it's here it has more of an angle up”).

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>BS1 begins annotating with text next to the Earth located in the summer. BS2 is now focused and studying the representation. BS2 studies the whiteboard intently.</td>
</tr>
</tbody>
</table>

(Continues)
The students continue to clarify their understanding, which involves differentiating the effect of the Earth's rotation (day and night) and orbit (seasons). In Episode 6, BS1 once again takes a lead in orchestrating an explanation using the drawing, the 3D model, gesture, and talk. BS2, having made the previous breakthrough, expresses accord (“Yeah”).

The self-monitoring of claims/ideas as the drawing proceeds, as well as the collaborative reasoning as the initiative passes back and forth between the boys, is evident at various points throughout this transcript. In an important sense, we can see the transcript as a coherent and unified line of exploration and reasoning even though at each point one or other of the pair is taking the pen and the initiative. We see again, in this example, the complex orchestration of multimodal representations (3D model, drawing, gesture, talk, and written text) involved in the reasoning process, in which drawing is a key part.

We note here, and it was evident in other tasks, the flexibility conferred by the whiteboard in encouraging early drafts and numerous redrafts as the students' understandings developed. In general, we noticed that when students were given these whiteboards, they were quicker to begin their speculative drawing and were able to negotiate more flexibly (compared with pen and paper) through shared control of both marker and eraser.

From Example 2.1, we argue that the drawing process was instrumental in shaping the students' visualizations, posing them with perspectival challenges (Peirce’s “doubt”) that they had to resolve. The affordance of the drawing process is here evident through the productive constraint offered by the
dimensional translation, as the boys had to consider the relation between the Earth's axial tilt, the angle of the Sun, and seasonal variation. The representational redescription process (Lehrer & Schauble, 2012) involved in translating between and orchestrating the 3D torch-Earth model, the gestural and verbal temporal narrative involved in representing the seasons, and the annotated drawing, involved a complex selection and abstraction process in establishing a productive perspective and a justified claim. Through this sampling process, the boys eventually realized that a possible productive visualization was to put two Earth positions at opposite ends of its orbit, and maintain a constant angle of the axis in space, thus modeling an explanation that was coherent and meaningful for them. This modeling process entailed addressing complex interlocking correspondence and coherence claims across 3D and 2D models, a process broadly consistent with science model-building beyond the science classroom.

We argue also for evidence of learning in this episode, in that through the drawing the boys came to understand (a) the relation between the Earth's tilt and the angle of the Sun in the sky, and (b) the representational moves needed to construct a coherent explanatory narrative that involved orchestration of the Earth's orbital position, as well as the axial tilt, in relation to the Sun's rays.

4 | DISCUSSION

Our purpose in this paper has been to identify, through micro-ethnographic analyses, the way drawing enacts a process of collaborative or individual reasoning, as an embedded part of the inquiry process. This discussion is structured around distinct aspects of the findings, which parallel the research questions: (a) the relationship between drawing and reasoning, from a socio-semiotic perspective, including its situation within multimodal inquiry; (b) the conditions under which drawing can enact reasoning and learning; and (c) the ways in which drawing supports reasoned interactions.

4.1 | RQ1: The different relations between drawing and reasoning

The examples demonstrated a variety of contexts and purposes for drawing within a multimodal inquiry setting. Students in most cases were actively engaged in the drawing process: constructing, evaluating, and collaboratively modifying their drawings to solve problems or construct explanations. We have argued that drawing can be an active process of reasoning, in which students engage in visuo-spatial claim making, evaluation through alignment with phenomena, often involving other modes, and modification in a collaborative or individual process of corepresentation.

4.1.1 | Drawing “as” reasoning; reasoning “through” drawing

Based on how students engaged with, speculated through, and fluidly monitored and refined their drawings, we consider it productive to think of drawing construction through a socio-semiotic framing involving speculative claim-making as abduction often through perception, and not easily reducible to linguistic reasoning. The drawing process can in this way be considered a form of knowing with varying degrees of conscious intention and design by the sign-maker. Accounts of Vygotsky (1981) mediation can sometimes position multimodal languages as a means, or a “tool”, toward a distinct cognitive end. But we prefer the more complex relationship that Peirce (1998b) posits between sign, signifier, and meaning, with the drawing intimately bound with the object of the drawing and the meaning ascribed to the relationship. In this way, students can be engaged in a drawing process before they are fully aware of their guiding assumptions, relevant background knowledge, or visual/spatial options (Cazden, 1981). This seemed to be most evident in the case of drawing with
whiteboards, where quick commitment to a mark, with repeated erasing, showed particularly the speculative and active claims and adjustments that were occurring. In argumentation terms (Toulmin, 1958), we consider the drawing as constituting a visuo-spatial “claim” that is accompanied by other claims, which might be verbal or embodied, to complete an argument. Thus, with the rapid marks and erasures, the back and forth between the 3D model and drawing, and talk, for the boys in Example 2.1, it is difficult to see the distinction between reasoning and perception (as Peirce pointed out). The drawing seemed to lead verbal articulation rather than proceed from it.

In taking this view, we recognize the difficulty in characterizing nonlinguistic processes through linguistic means, and the strong tradition in science education of viewing reasoning as predominantly logic-based thinking “in the head” and linguistic in nature, which seems to be the result of a “classical logic” (Woods, 2013, p. 17) at play that frames what counts as legitimate reasoning. We choose to talk of drawing as “enacting” reasoning when it entails making a visual claim, and the drawing process “as” reasoning. Rather than drawing playing a role that helps us “to” reason or which simply “expresses” our reasoning.

4.1.2 | Forms of reasoning through drawing

The variety of reasoning moves supported by representational work is a feature of previous research (Cox, 1999; Greeno & Hall, 1997; Kirsh, 2010). We have shown how reasoning through and with representation construction occurred at many stages in science classroom investigations; from planning investigations, recording, to analyzing/interpreting data (Tytler et al., 2013).

In the current study, the micro-ethnographic analysis has allowed a more detailed account of some of the forms of reasoning opened up through drawing. Focusing on the selected examples, these forms of reasoning through drawing include multiple forms of model-based reasoning, where students addressed complex challenges around making and assessing correspondence and coherence claims. Correspondence-claiming and checking were evident as students sought to establish alignment between phenomena and their drawings (the mousetrap car and flower examples), and between models (the flower and astronomy examples). Coherence-claiming and checking were evident in students’ proto-modeling of the mousetrap car mechanism and in developing a model of the Earth’s orbit and tilt in the astronomy example. In initial stages, drawings functioned as exploratory and fluid sampling of possible visuo-spatial claims by individually or collaboratively by groups. In this process, the particular affordances of drawing were clear, in relation to other modes. The visual and spatial specificity of the 2D drawing productively constrained student attention (Prain & Tytler, 2012) and made demands on their observations and imaginative speculation, involving a two-way mapping process between the drawing and the phenomenon (the flower) or model (the Earth globe). While the accompanying gesture and talk, or material exploration supported this process, in these examples, the drawing played a unique role within these multi modal assemblages. Drawing therefore can play a part in the necessary role of “transduction” (Volkwyn, Airey, Gregorič, & Heijkenskjöld, 2016) in science learning. This is understood as the imaginative process whereby learners remake the meaning of a sign in one mode into a sign in a different mode.

4.1.3 | Reasoning “from” drawing

The other aspect of drawing is its ongoing presence as an object that can be inspected, assessed, and revised. Here, we can consider reasoning “from” drawing that can serve similar functions. An example would be activities where different students' drawings are displayed, discussed, and evaluated for
fit (Tytler et al., 2013). An example is the collaborative reasoning processes in the astronomy Example 2.1 that centered on the developing drawing. Here, we had a complex movement of reasoning through and from drawing as the boys took turns to create, compare across modes, inspect, and evaluate their developing drawing.

Drawing has these dual roles, and with them, two faces to reasoning that are made evident by the socio-semiotic approach. Reasoning “through” drawing is aligned with Magnani’s (2013) articulation of the “unveiling” role of drawings. In cases such as the fast, fluid, and collaborative reasoning through drawing in Example 2.1, which led to new visualization of the spatial and temporal relations that enabled sense to be made of the seasonal variation in the Sun’s angle, the “various zooming effects of spatial reasoning” that Magnani (2013, p. 324) alludes to are seemingly at play. Reasoning “from” drawing is also evident as the boys in Example 2.1 modified their explanatory talk and the drawing, in response to inspecting and evaluating it. This broadly aligns with Magnani’s (2013) consideration of the “mirror” role of drawings, where the drawing as an object can be held up for inspection, to consider its explanatory alignment with the target phenomenon.

4.1.4 | Drawing within a multimodal orchestration

Concerning the multimodality of scientific knowledge building, the examples illustrate that drawing to reason in an open inquiry context always occurs in concert with other modal processes. Students reasoned through drawing, but the establishment of meaning involved orchestration across verbal and gestural claims, annotation, and exploration through material manipulation including 3D model manipulation. We argue that while drawing through its particular visual and spatial affordances opens up powerfully fresh perspectives, its meaning is always situated alongside other modal claims, distributing knowledge across the multiple models and symbolic language forms needed to make sense of the world. This claim is consistent with a large body of research into the multimodal nature of science teaching and learning (Kress & van Leeuwen, 2006; Lemke, 2004), expert problem-solving (Gilbert, 2005; Kozma, 2003; Kozma & Russell, 1997), and knowledge creation in the discipline (Gooding, 2006). However, what we have shown in micro-ethnographic detail in this study is how drawing enacts and supports reasoning in cooperation with these modes. In many of the examples for instance, we can see the importance of gesture in establishing correspondence and coherence as students identify key components of the phenomena for themselves, and coordinate their multimodal claim-making.

4.2 | RQ2: Conditions under which drawing supports reasoning and learning

Our examples indicate that multiple conditions need to be met for student drawing to enact and support reasoning and learning. These include: the nature of the drawing challenge, students’ prior understandings and experiences, and teacher support throughout the process.

First, the challenge needs to be framed such that students are encouraged to approach the drawing as a reasoning process where they can interpret, explain, or make a claim about a process or phenomena, and where drawing prompts and clarifies thinking. In some of the toy challenges for instance, students explored the material features and developed a resolved understanding of mechanisms, where the drawing was not perceived as claim-making. Based on the examples where the drawing supported reasoning, we suggest that the nature of the challenge should encourage students to coordinate, integrate, or synthesize past/partial representations (understandings) rather than simply applying a known representation to a new situation. The challenge will entail student reasoning to establish
adequacy of correspondence with the referents, and internal coherence of claim(s) as a model or proto-model. The challenge should also suit the specific affordances of drawing (abstraction, specificity, spatial distribution of key parts, productive space constraints, correspondence- and coherence-making, and checking). The challenge should be sufficiently open to allow diverse representations, rather than one “correct” account, promoting further guided analyses and representational refinement. The challenge should focus on a sufficiently clear problem to enable students to judge their degree of success, and see the value of drawing as a form of reasoning.

As a second condition, students needed adequate background knowledge of the science content and of relevant representational conventions to enact their claim-making. Thus in the flower session, in many cases, students had insufficient grasp of reproductive processes to enable a coherent proto-modeling process that aligned their flower structures with the idealized model. In some of the astronomy examples, students had difficulty translating from the 3D model to a 2D proto-model that satisfied the necessary correspondence and coherence conditions.

This study focused mainly on independent student reasoning, but the teacher has a crucial role in structuring challenges that are meaningfully contextualized for students, entail inquiries that students wish to understand more deeply, and are suited to their current topic understandings and representational competence. Teachers involved in this study were constrained by the single lesson format but nevertheless introduced representational conventions relevant to the tasks, and circulated to provide ongoing support, scaffolding and feedback as part of the inquiry process. In previous research involving longer term classroom sequences, teachers provided support for all stages of these representational challenges, and guided students to learn to evaluate the adequacy or comprehensiveness of their own, peer, and textbook representations (Tytler et al., 2013).

4.3 | RQ3: Drawing as self-checking and corepresentation

By corepresentation, we mean the process and product of meaning-sharing or alignment of understanding between students. There were many examples in the data of students reasoning collaboratively through the drawing process, and we drew attention to the inspectable nature of the drawing as key to this; for pairs or groups of students, for the teacher and students, and for individuals as they monitored and adjusted their drawing claims “on the fly.” The function of drawing for individual monitoring or “self-checking” has been previously described (Ainsworth et al., 2011; Van Meter & Garner, 2005). Here, from our socio-semiotic perspective, we emphasize the importance of the drawing as part of a distributed representational system through which reasoning proceeds.

The evidence for drawing as “coconstructive” is particularly clear from Example 2.1, which is illustrative of further examples where students shared the drawing task, either taking turns with the pen, working with more than one whiteboard marker, or often sharing the conceptual task with the nondrawing partner working through another mode (observing, commenting, or in the case of astronomy exploring the 3D model as their partner performed the 3D–2D translation). We argue, further, that the drawing process was a case of “corepresentation” in the sense that there seemed to be a close negotiation across multiple modes, including language (verbal and written), material objects, and in the astronomy example 3D models, such that students achieved a coordination of views that was quite specific to the problem at-hand. We do not presume to know exactly the degree of alignment of understandings for participants, but for instance in Example 2.1, the drawing negotiation involved a shared process of imaginative projection involving very specific adjustments in the drawing of the Earth’s positioning and tilt. If we consider the way the exploratory/explanatory narrative unfolded in that case, it represents a coherent development of visual, spatial, and verbal claims through multiple
inputs and adjustments in which the two students switched the lead at various times. It was as if, through these cross-modal constructive processes, they were speaking and acting with a shared voice. Within this shared construction process, the drawing placed specific demands on the establishment of meaning, for instance, in the detailed negotiation of the Earth's positioning and axial tilt. Because of its visual and spatial specificity, its abstract and symbolic potentiality, and its tangibility allowing for ongoing inspection, drawing played an important role in this process of “settling” understanding in each example. These understandings find form, following Latour (1999), as inscriptions that are portable and reified, and open to communal inspection.

5 | CONCLUSIONS

In this study, we have identified both multiple conditions and multiple opportunities for drawing to enact and enable student reasoning. These conditions include (a) effective use of the particular semiotic affordances of drawing for new sign-making, swift revision, and inspection within a multimodal context, and (b) pedagogical conditions for effective learning with and from drawing. Our micro-ethnographic study extends the past literature on claimed semiotic affordances of drawing by: (a) demonstrating the complex ways in which these particular affordances play out in relation to reasoning in different drawing contexts, and (b) confirming empirically their putative value and roles in this student learning. While all semiotic modes in persuasive scientific explanations are expected to address the criteria of correspondence and coherence, we noted the particular felicities of drawing as an improvised, imaginative, flexible way to engage with this double challenge, as demonstrated in the case studies. The identified pedagogical conditions include the precise nature of the drawing challenge and its fit to the conceptual challenges of the topic, students’ prior understandings of the topic and drawing experiences, and their orientation to the drawing challenge as claim-making, and teacher support throughout the process. We consider that the presence or absence of these conditions may in part account for past mixed findings in research on learning from drawing.

In analyzing temporal and contextual aspects to these case studies, we also identified multiple opportunities for where, when, how, and why student drawing enacted and enabled reasoning. Students reasoned before, through, and from drawing, and in the astronomy case constructed a collaborative drawing that enabled participant students to check their understanding as they corepresented claims. These findings extend the current broad case for learning opportunities arising from student drawing. To be clear, we are not claiming that drawing is the most important resource for transmodal reasoning, but rather that this mode can make a distinctive and valuable contribution among other modes to science learning.

This micro-ethnographic study entailed a tightly structured set of open tasks with collaborative reasoning being tracked using multiple cameras and audio channels. The method had attendant limitations on tracking learning including the lack of extended topic sequences with teacher control, and the lack of opportunity to establish learning “outcomes” through more traditional means. Further research into drawing as a constructive, inquiry process should extend these findings to in-depth investigation of the multiple roles of drawing in sequences of classroom-based challenge tasks, and teacher scaffolding that lead to robust learning. This research has shown ways in which reasoning processes with and through drawing vary considerably across different contexts and topics, varied student knowledge and intentions, and review processes. It opens up the need, and also provides a framework to investigate further how drawing can enable learning across multiple topics and contexts. In identifying in detail how the affordances of drawing enable student reasoning under particular conditions, we have sought to contribute to how this future research agenda can be conceptualized and further investigated.
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