How to cite:
Park, J., Tang, K. S., & Chang, J. Plan-Draw-Evaluate (PDE) pattern in students' collaborative drawing: Interaction between visual and verbal modes of representation. *Science Education*, 1-33.

Plan-Draw-Evaluate (PDE) pattern in students' collaborative drawing: Interaction between visual and verbal modes of representation

Joonhyeong Park[12], Kok-Sing Tang[1], Jina Chang[13]

[1]School of Education, Curtin University, Perth, Australia

[2] National Institute of Education, Nanyang Technological University, Singapore, Singapore

[3] Seoul Seongil Elementary School, Seoul, Republic of Korea

Correspondence: Joonhyeong Park, National Institute of Education,

Nanyang Technological University, 1 Nanyand Walk, Singapore 637616

Email: joonhyeong.park@nie.edu.sg

Plan-Draw-Evaluate (PDE) pattern in students' collaborative drawing: Interaction between visual and verbal modes of representation

Abstract

The use of group drawing to promote student-generated representation is a common instructional strategy as it combines the benefits of using visual representation and collaborative talk. Although the affordances of group drawing have increasingly been emphasized in science education, few studies have investigated how drawing as a visual mode interacts with group discourse as a verbal mode as well as how that interaction facilitates the development of students' collective ideas. Informed by theories in classroom discourse and multimodality, this paper examines the interaction process between a verbal and visual mode of representation as groups of students engaged in collaborative drawing during guided science inquiry lessons. Based on the analysis of data from a science class that adopted group drawing, we found and documented a recurring pattern, Plan-Draw-Evaluate or PDE pattern, in how the interaction between the verbal and visual modes occurred during collaborative drawing. This PDE pattern consisted of a triad of moves that alternate between the two modes and fulfilled various discursive purposes, such as suggesting, requesting, recording, visualizing, elaborating, agreeing, and rejecting. The PDE pattern provided a basic social structure that facilitated the collaboration and progression of students' ideas. With illustrations of PDE patterns and its variations, we argue that the PDE pattern provides an insight into the dynamic organization of interactions involved in group drawing that takes into consideration the multimodal affordances of verbal and visual modes of representation and the progression of ideas developed through collaborative discourse.

Keywords: collaborative drawing, student-generated drawing, visual and verbal modes, discourse

1. Introduction

There has been a growing attention paid to student-generated drawing to support science learning (Prain & Tytler, 2012). In science education, the benefits of student-generated drawing have been reported in terms of fostering conceptual understanding (e.g., Brooks, 2009), reasoning (e.g., Fan, 2015; Quillin & Thomas, 2015), communication (e.g., Ehrlén, 2008), and scientific literacy (Knain, 2006). As such, current research in science education is exploring new pedagogical approaches with a focus on student-generated drawing. Such a pedagogical approach in general involves students in constructing, negotiating, and refining drawings—as a form of visual representation—in a guided science inquiry process (Tytler, Prain, Hubber, & Waldrip, 2013).

The affordances of group drawing, such as allowing the integration of multiple representations and providing opportunities for joint reasoning, have been argued by several researchers (e.g., Gijlers, Weinberger, van Dijk, Bollen, & van Joolingen, 2013; Prain & Tytler, 2012; Scheiter, Schleinschok, & Ainsworth, 2017; Tytler, Prain, Aranda, Ferguson, & Gorur, 2020; van Dijk, Gijlers, & Weinberger, 2014). Theoretically, group drawing combines the benefits of using visual representation and collaborative discourse. Not only are students given opportunities to discuss their ideas verbally, but they also record and make explicit their ideas on a permanent medium (e.g., paper, screen), which serves as a public space to prompt and facilitate further dialogue (Parnafes, 2012). This mutual interaction between students in collaborative discourse, as well as between a verbal and visual mode of representation in drawing, is a major factor that shapes the effectiveness of most student-generated drawing approaches.

Despite the general consensus that group drawing has many affordances, the detailed mechanism of how student-generated drawing occurs through group interaction is not yet well understood. In particular, as collaborative discourse is predominantly mediated through a verbal mode of representation while drawing is largely a visual mode, how these two different semiotic modes interact multimodally at a turn-by-turn basis has not been investigated. There is a lack of

studies that examine how students coordinate verbal dialogue with the construction of their drawings as they engage in a collaborative discourse at a micro-genetic level. A fine grainsize level of analysis of this investigation allows us to closely capture how students think and respond to the ongoing developing ideas sensitively in dynamic interactions (Parnafes, & diSessa, 2013; Tang, Delgado, & Moje, 2014). Thus, this level of examination may contribute to revealing the interactions involved in group drawing. Based on the understanding of this interaction, we can advance our knowledge of how students learn from group drawing as well as support teachers in promoting student-generated drawing through a guided inquiry approach.

The purpose of the study reported in this paper is thus to investigate the interaction process between the verbal and visual mode of representation in collaborative drawing. The verbal mode involves students talking to one another through moment-by-moment interactions while the visual mode involves students drawing together to generate a visual representation of their ongoing explanation of a scientific phenomenon. These two modes do not occur independently of each other, but rather combine in complex ways to mediate students' development of ideas through group drawing. As such, the broad research question that guided this study was: How do the verbal and visual modes of representation interact with one another in students' collaborative drawing?

This study revealed a recurring pattern in how the verbal-visual interaction occurred through a repeated sequence of planning, drawing, and evaluating by fifth-sixth grade students who were asked to construct scientific explanations in small groups. This Plan-Draw-Evaluate or PDE pattern consists of a basic triad of moves that serve various discursive purposes (e.g., suggesting, focusing, recording, visualizing, elaborating, agreeing, and rejecting). Through various illustrations presented in this paper, we argue that the PDE pattern provides an insight into the dynamic organization of group drawing considering the multimodal affordances in relation to the progression of ideas developed through collaborative discourse.

2. Theoretical background

The theoretical basis of this study is based on a synthesis of three well-established research areas in science education: classroom discourse, multimodality, and student-generated drawing. Classroom discourse provides the theoretical lens to examine the verbal interaction and collaboration among the participants involved in a group drawing activity, while multimodality provides the lens to examine the interaction between the verbal and visual mode of representation as the students produce a group drawing together. As an area of interest within these two theoretical foundations, the focus on student-generated drawing further provides a research perspective of drawings' affordances and constraints as well as its pedagogical approach as a guided inquiry.

2.1 Interaction between participants in classroom discourse

Research in classroom discourse has developed a range of conceptual and analytical tools to understand how classroom activities are structured through talk. Informed by research traditions in ethnomethodology (Garfinkel, 1967) and conversation analysis (Sacks, Schegloff, & Jefferson, 1974), researchers have paid attention to the discursive role of language in shaping classroom activities. Early research focused on how teachers use verbal language to facilitate their interaction with their students in class discussion. One crucial finding was the revelation of an interaction pattern that consists of three moves: a teacher initiates (I) a question, a student gives a response (R), and the teacher evaluates (E) the student's response (Mehan, 1979). In general, research in this area has revealed that classroom discourse consists of a number of characteristic patterns that facilitate the participation and meaning-making interaction among the teachers and students (Tang, 2020).

The revelation of interaction pattern in classroom discourse brings about a new way of improving science pedagogy through teacher questioning (Chin, 2007). For instance, the IRE (Initiate, Response, Evaluate) pattern was found to be controlling and authoritative as it limits

students' responses to a narrow range of right and wrong answers (Lemke, 1990). However, by making a small change in the last move from an Evaluate (E) to a range of "Follow-up" (F) moves, researchers have shown that this can lead to a more dialogic conversation that incorporates students' voices (Mortimer & Scott, 2003). Some examples of good follow-up moves include revoicing (O'Connor & Michaels, 1993), reflective toss (Van Zee & Minstrell, 1997), and constructive challenge (Chin, 2007). This development shows the importance of examining and understanding interaction patterns in classroom discourse.

Besides the interaction patterns that are led by a teacher, research in classroom discourse has also examined collaborative discourse among students in small groups. One of the main concerns among researchers in these studies has been to understand how different communicative structures function in terms of promoting joint construction of knowledge (Mercer, 2004). Based on this concern, various dialogic approaches have been developed to understand conversation from a co-constructive perspective (e.g., Kelly, Brown, & Crawford, 2000; Scott, Mortimer, & Aguiar, 2006; Tang, 2017). For example, Wells (2001) describes a co-constructive interaction pattern between two group members in the form of Demand-Give-Acknowledge (DGA), which involves one member demanding a response for co-construction, the other member giving a response, and the first member or another member acknowledging the response.

In addition, studies of argumentative discourse in small groups, such as Toulmin's Argument Pattern (TAP), have also extended the understanding of collaborative conversation and helped students to build a constructive dialogue (Erduran, Simon, & Osborne, 2004). Collectively, recent work in this area has developed analytical tools to examine collaborative discourse using general interaction patterns such as question and answer, give and accept, and statement and acknowledgement. Using these interactive patterns, various instructional approaches have been developed to support students' collaborative learning in small groups, given that teachers or facilitators can play a crucial role in shaping group activities with metacognitive questioning and

encouragement (Hmelo-Silver & Barrows, 2008) considering the sociocultural contexts and purposes of the group work. For example, when teachers see students who are quiet or passive, teachers can give them opportunities to develop and practice discursive skills (Radinsky, Oliva, & Alamar, 2010). However, most studies in collaborative discourse and the instructions they have provided have focused mainly on verbal interaction and did not incorporate a visual mode of representation in their conceptual and analytical framework. Thus, we aim to address this gap by studying students' group drawing at the discursive moment when they embark in a collaborative discourse.

2.2 Interaction between verbal and visual modes of representation in science classroom

Research on visual representations in science education generally falls under two dominant perspectives, as framed under the terms "multiple representations" and "multimodality" (Prain & Waldrip, 2006; Tang, Tan, & Yeo, 2011). According to Tang et al. (2014), multiple representations research views representation as a form of instructional artifact at a large "grain size", such as a written text passage or picture in a textbook, and seeks to examine learning gain from each representation or a combination of verbal-visual representations (e.g., Ainsworth, 2006; Schnotz, 2005). On the other hand, multimodality tends to examine the meaning-making process mediated by a discursive coordination of multiple modes, such as talking, writing, gesturing, and drawing (e.g., Kress, Jewitt, Ogborn, & Charalampos, 2014).

Research related to multiple representations is generally informed by various cognitive theories, such as the cognitive theory of multimedia learning (e.g., Mayer, 1997), cognitive load theory (Chandler & Sweller, 1996) and the integrated model of text and picture comprehension (ITPC; e.g., Schnotz 2005). Previous research supports the benefits of simultaneously presenting verbal and visual information. The theories assume that different modes convey qualitatively different information so that they can play a complementary role within a proper instruction;

verbal mode describes materials in an interpreted and abstracted manner while visual mode depicts the materials in relation to our visual sensory experience (Mayer, 2009). In addition, as information from each mode is processed in different cognitive channels, this facilitates the working memory to build connections between the words and pictures (Horz & Schnotz, 2008). If these modes function and are integrated into a complementary relationship, it leads learners to construct deeper understanding based on this integration (Ainsworth, 2006). Studies in this area typically uses individual think-aloud and quasi-experiments to document learning gain. While they reveal the relative benefits of using a verbal and/or visual mode, the research does not take into account the dynamic and micro-genetic mechanism of verbal-visual interaction involved in collaborative discourse, which is the focus in this paper.

In contrast, research in multimodality examines a range of modes (e.g., verbal language, image, gesture) that mediate human communication and has developed a range of theoretical tools to understand how meaning-making in communication proceeds by using these modes. This area of research is generally informed by social semiotic theories that conceptualizes a *mode* as a cultural system of resource that people draw upon to make meaning within a community (Halliday, 1978; Kress & van Leeuwen, 2006, Peirce, 1986). Researchers in social semiotics have increasingly extended their view from exploring the affordances of individual modes to examining the integration or combination of modes that are used in scientific meaning-making. As each mode has different affordances in making different kind of meanings, the meaning potential "multiplies" when they are combined in an interaction (Lemke, 1998).

Multimodal meaning-making in the science classroom is often investigated from a discourse perspective in terms of the discursive interaction of coordinating talk, gesture, and other modes of representation (Tang et al., 2014). In order to investigate conversation in the science classroom, recent research has used a micro-genetic approach that allows a closer examination of how the discourse progresses turn-by-turn as the utterances made by the participants unfolded (e.g., Jaipal,

2009; Kress et al., 2014; Maeng & Kim, 2011; Park & Song, 2020; Tang et al., 2011; Xu, Ferguson, & Tytler, 2020). In particular, researchers have paid attention to how conversation is shaped and built using multiple modes such as spoken language, physical actions, and so on, focusing on how these modes combine in the meaning-making process. In this type of multimodal discourse, multiple modes of representation, such as diagrams, written texts, and mathematical equations, are also employed and interact with each other to extend and to scaffold multimodal discourse as a meaning-making process (Jaipal, 2009).

An important consideration in theorizing the interaction between multiple modes of representation within classroom discourse is to track the continuity or progression of ideas as they emerged dynamically through the multimodal interaction. There is where the concept of intertextuality (Lemke, 1992) based on the theoretical ideas of Bakhtin's (1986) dialogism becomes useful for our purpose. Intertextuality is the idea that every utterance or text appears in a continual dialogue that has historicity within a chain of meanings. Thus, each utterance or text in continual discourse should be understood in its historical context. Based on this concept, several studies have investigated students' progression of ideas through an intertextual connection across different modes of representation, such as the verbal and visual modes, in science classroom (e.g., Tang et al., 2011; Yeo & Gilbert, 2017).

Research from multimodality has generally shown how students make meanings at a discursive moment by combining talk and gestures with pre-existing diagrams that are taken from curricular materials (e.g., textbooks, worksheets). However, few research has explored the meaning-making process as and when new diagrams are generated by students at a micro-genetic level. This is where we synthesize this area with the emerging research on student-generated drawing.

2.3 Student-generated drawings as science learning

Based on the theoretical basis of classroom discourse and multimodality, research in student-generated drawings has identified the roles and functions of drawings in shaping science learning as well as developed instructional approaches considering its affordances and constraints. The meaning-making process of drawing activities in science classroom has been also examined by social semiotic theories and modeling perspectives to support students' science learning.

In terms of drawings' roles, one of the main findings of the research is that the act of drawing affords the integration of multiple modes of representation, including verbal and visual modes, that can contribute to students' meaning-making as they learn science, thus allowing them to be an active learner (e.g., Parnafes, 2012). According to the generative theory of drawing construction (Van Meter & Garner, 2005), verbal content is firstly organized into a coherent representation and then visual representations are constructed based on the verbal foundation that involves selecting visual contents to be included. Furthermore, constructed external visual representation plays a communicative role as a self-explanation to review and check their understanding in a coherent manner. It also functions as a medium to build discursive discourse with peers and teacher that encourages students to share and elaborate their ideas concerning their verbal representation (Parnafes, 2012; Schwartz, 1995). From this integrative role of drawings, researchers have investigated how drawings orchestrate multimodal representation, including visual and gestural modes of representation in learning science (e.g., Tytler et al., 2020). In addition, researchers have also expanded their interest in drawings' mediums from paper-and-pencil to various technologies (Cromley, Du, & Dane, 2020), such as in web-based collaborative drawings.

Regarding instructional approaches, there is a consensus that students' drawings should be sufficiently guided in instructions (Fiorella & Zhang, 2018; Schwamborn et al., 2011). Research in this area has been approached as a guided science inquiry process such as providing detailed scripts to guide students' collaborative drawings (Gijlers et al., 2013; van Dijk et al., 2014), giving

opportunities to activate their prior knowledge (Van Meter & Firetto, 2013) and presenting concrete comments and questions to students to improve their visibilities of drawing (Quillin & Thomas, 2015). The detailed pedagogical supports for students' drawings would contribute to involving various and complex resources from students' prior knowledge in their learning (Fiorella & Zhang, 2018). Although this initiation in drawing activities can enhance metacognitive functions and self-regulation of students to learn science (Scheiter et al., 2017), students who have insufficient understanding of the contents to be represented and prior knowledge may confront difficulties to reveal their unclear ideas visually and explicitly. Thus, researchers have also paid their attention about how student-generated drawings in a guided inquiry support student's learning considering their prior knowledge and capabilities.

According to social semiotics theories, constructing external visual representation is not just merely drawings but a process of meaning-making, including visual reasoning. Especially, since a particular community has its communicative system of visual signs and symbols that can represent conventional and specific meanings (Kress & van Leeuwen, 2006; Lemke, 1990), students who are asked to draw diagrams in learning science should organize and coordinate their representation of scientific concepts and visual reasoning in a scientific way. The efforts in the generation process thus contribute to refining their conceptual understanding because drawing diagrams demands students to represent more specific conceptions (Stenning & Oberlander, 1995). For example, as shown in Prain and Tytler's (2012) study, all students who were asked to draw what happens in evaporation of water could adopt a molecular explanation. Recent studies have also examined analyzing students' representational competence using drawing technology across different topics (Chang, 2018) as well as developing analytical frameworks to understand the various meanings made in student-generated drawings (Tang, Won, & Treagust, 2019).

Since generating scientific drawings in science education usually aims to allow learners to construct and elaborate their own explanations, the act of drawing has also been regarded as a

modeling practice that can be used to coherently explain scientific phenomena in science education (Gilbert & Justi, 2016). In particular, research from this perspective has reported that students in a group create, test, and modify their model through a consensus process that is a key element of modeling practice (Blanco-Anaya, Justi, & Díaz de Bustamante, 2017; Lehrer & Schauble, 2012; Tytler et al., 2020). In addition, drawing a scientific diagram has also been found to prompt model-based reasoning in order to understand scientific phenomena through making sense of the phenomena and articulating an explanation (Kawasaki, Rupert Herrenkohl, & Yeary, 2004; Quillin & Thomas, 2015). For example, drawing a molecular level view to explain and predict scientific phenomena such as dissolving and bonding can be used as a tool to support model-based reasoning (Cooper, Stieff, & DeSutter, 2017). Although the features of drawing have many commonalities with the features of modeling, these commonalities cannot always be seen if we follow the rigorous definition of modeling.

Research in scientific modeling has shown that external representation should be abstracted from phenomena in a coherent relationship with related concepts and the drawn model should show particular data patterns (Passmore, Stewart, & Cartier, 2009). In addition, the practice of modeling should involve four elements: constructing, using, evaluating, and revising (Schwarz et al., 2009). Unless the purpose of specific drawings can be shared with this definition, where there are still commonalities, it is difficult to always consider drawings to be modeling. For example, a diagram of a falling stone and its movement is a drawing, but it may not be regarded as a model, because it does not provide any abstracted structure or mechanism of phenomena and relationships with further related scientific concepts. Considering the case of this example and a wider definition of modeling, we believe there is room for further discussion on the relationship between drawing and modeling to support students' science learning through construction of scientific explanations and models. Since few studies have investigated students' drawing activities guided by model-based instruction in a moment-by-moment manner, this study aims to provide a

basis of the practical and theoretical knowledge for this discussion of the relationship between drawing and modeling and how group drawing activities can be supported by model-based teaching in science learning.

In summary, even though there is ample research in collaborative discourse, verbal-visual coordination and student-generated drawings, current understanding in this area is limited to the generative function of using visual representation (e.g., as a permanent record) in collaborative works and the usefulness of student-generated drawing as a pedagogical strategy. Few studies in this area have focused on the interaction process at a micro-genetic level (i.e., moment by moment) that would shed light on the mechanism of how students generate drawings as they talk to one another in small groups. This level of discourse analysis is a useful approach to track trajectories of students' meaning-making process (Opfer & Siegle, 2004) and reveal certain patterns about their dynamic interactions (Parnafes, & diSessa, 2013). In particular, no research has shown the interaction patterns and how they emerge in group works involving both the interactions among members as well as between verbal and visual modes of representation. In this regard, this study aimed to examine patterns of both sets of interaction using a micro-genetic level of analysis.

3. Research method

3.1 Research context and design

The data for this study were taken from a larger classroom research that developed and enacted a pedagogical approach focusing on student-generated drawings. In this approach, students constructed visual representations to support their ongoing understanding and explanation of physics phenomena. In order to scrutinize students' construction of drawings, both individual and group drawings were used and investigated in the research project. Initially, individual processes in drawing were explored in relation to how the students generated their own drawings in terms of

different representational levels and how to guide them to represent their ongoing understanding (Chang et al., 2020; Park et al., 2020). In the later part of the project, which is the focus of this study, we examined the process of group drawing in terms of their collaborative discourse and how to support them to generate group diagrams.

For the purpose of this study, we use an instrumental case study (Stake, 2000) to generate insights or draw inference on an issue (e.g., group drawing) based on a certain case, as opposed to an intrinsic case study to better understand the particular case itself. Based on the analysis of the chosen case, this study aims to investigate the mechanism of group drawing activity, which has affordances involving interaction between verbal and visual modes of representation and interaction among the participants. Similar to the interaction patterns involved in classroom discourse, such as the IRE, IRF, or DGA patterns that we noted in the literature review, group drawing activity may also involve specific interaction patterns or structures. We thus focused on finding interactions patterns through a micro-genetic approach rather identifying the distribution of patterns, in order to generate insight from the findings. Given this context and design, the specific research questions that guided this study were formulated as follow:

1. What patterns of interactions between visual and verbal modes of representation can be identified within a collaborative drawing activity?
2. How do verbal and visual modes play complementary roles in students' development of ideas?

During the study, we did not assume or prescribe any specific interaction pattern for the students' collaborative discourse. It was only in the analysis that we probe for patterns in an inductive way and then examined the interaction patterns that emerged from our analysis. In order

to investigate these interaction patterns, we focused on alternation between the two modes and each mode's role in terms of their complementary relationship.

3.2 Participants

Fifteen fifth and sixth grade students who were 10 to 12 years old were observed in three lessons in a gifted science classroom in Australia. The selection of the students, who were active learners with many experiences of group work, was important for our purpose of focusing on the interaction between visual and verbal modes based on their collaboration in this study. The topic of the three lessons was sound transmission, and the main inquiry questions were "How sound can be transmitted from one tuning fork to the other tuning fork in the air?" in lesson 1, "How can sound be transmitted through a spring and a paper cup?" in lesson 2, and "How can the different thicknesses of rubber bands make sounds that have different pitches?" in lesson 3. For each lesson, the students were asked to construct a group diagram using pencils and erasers on one worksheet, which was A3 size and had four blank sections, as part of their responses to the main inquiry question located on the top of the paper. There were five groups of three students for each drawing activity (Table 1). The classes were in the fourth term and according to the teacher, the students were willing to work together and often formed positive relationships with one another. In order to help them collaborate, they were asked to discuss how to draw together. For example, they shared ideas about the importance of consensus when drawing as a group and ways of collaboration. During the five weeks of their program previous to the study, they answered questions about air and water pressures individually by drawing and writing, which may have familiarized them with drawing scientific diagrams.

Table 1 Groups in the study

	Group 1	Group 2	Group 3	Group 4	Group 5
Students' codes	G1S1, G1S2, G1S3	G2S1, G2S2, G2S3	G3S1, G3S2, G3S3	G4S1, G4S2, G4S3	G5S1, G5S2, G5S3
Gender	3 boys	2 boys, 1 girl	2 boys, 1 girl	2 boys, 1 girl	3 boys

3.3 Data collection

The qualitative data in this study came from five video cameras and audio recorders, one for each group in each of the three lessons, and fifteen group diagrams of worksheets. The three authors of this paper (R1, R2, and R3) took part as participant-observers during the data collection. They asked questions to each group to understand the meanings of their drawings and help the students developed their explanations, but not to the point of giving answers to the main questions. At the same time, they also wrote field notes of interesting or recurring classroom events. We collected the whole teaching sequence of the lesson, which involved teacher instruction, brainstorming, drawing, and written explanation. Students developed their explanation verbally first during a brainstorming session after the teacher's instruction and hands-on activity, which involved a Predict-Observe-Explain (POE) instruction (White & Gunstone, 1992). They then constructed their explanation with the aid of a group drawing. Finally, students summarized explanation by individual written text. The drawing process was the main object of analysis so the researchers analyzed this data within the context of the lesson flow.

3.4 Data analysis

Analysis process

The analysis was carried out in two steps. First, to investigate the interaction between the visual and verbal modes, we followed the micro-genetic analysis approach outlined by Wells (2001) to

examine the discourse in a discursive turn-by-turn manner. Using this approach, we developed an analytic framework to analyze the interaction between the visual and verbal modes in the students' dialogues. In accordance with this framework, at first, we inductively looked for emerging interaction patterns guided by the constant comparison method (Merriam, 1998) and then complemented the emerged pattern with the existing framework. Specifically, the first author extracted several initial interaction patterns, arranging the features of each mode, such as organizing, agreeing, suggesting, and planning for the verbal mode and generating, adding, coloring, and drawing for visual mode, based on the corpus of data. The other authors then reviewed the patterns together with the video/audio data and students' drawings regarding the functional categories of discourse suggested by Wells (2001) focused on the context of collaborative drawing. For reliability, we repeated this process and refined the patterns iteratively until we had consensus on the interaction patterns.

Second, based on our understanding of the interaction patterns, we then interpreted how the two modes – verbal and visual – played complementary roles in the development of the drawings using the constant comparison method (Merriam, 1998). For this, we determined the roles of each mode and interpreted the progress of the students' ideas in the group drawings through the lens of intertextuality (Lemke, 1992) as the meanings alternate between the verbal and visual modes. In addition, to identify the incremental progress based on this alternation, identification analysis based on systemic functional linguistics (Martin & Rose, 2007) was used, involving tracking participants and textual resources in a discourse. The analysis involves two types of tracking: using pronouns to identify the subject of the conversation (e.g., person, thing) and using scientific terms or diagrams to identify how students develop their conceptual ideas (For elaboration, see Tang & Tan, 2017). Tracking pronouns was done in a verbal mode, while tracking scientific representations was done in both verbal and visual modes. The developmental levels of the tracked pronouns and scientific representations were analyzed in terms of how elaborated and

specific the subsequent pronouns and representations have become. For instance, if the first identified pronoun 'that' refers to 'particles' and the second identified pronoun 'that' indicates 'air molecules' happens a few turns later in a collaborative discourse, the authors agreed that the second tracked pronoun has shown a higher specificity of the 'particle,' which is a developmental idea along with the discourse flow. Given the context of the discourse, the meanings of students' collaborative drawings and their scientific terms were also tracked and analyzed in the same approach. The authors went through this process five times before coming to an agreement on the interpretation.

Analytic framework: Encompassing drawing (visual mode) in discourse analysis framework

In order to analyze the discursive (moment by moment) interaction between the visual and verbal modes, first we had to make a decision on how to incorporate students' drawing (as a visual mode of discourse) in a verbally focused discourse analysis framework. To involve the visual mode into a typical discourse analysis framework, we chose to represent each participant's action on a vertical line rather than horizontally, while maintaining a turn as either an utterance or a moment of drawing from any participant. This method allows the representation of concurrent visual and verbal modes as they occurred in the transcript. These were spontaneous events that frequently happened due to the affordances of group drawing where students can talk to one another while one student is drawing.

Another decision we made was how to represent the act of drawing in the transcript. First, the authors reached an agreement that a moment of drawing started with a pencil touching the paper and ended with the completion of a drawing or scribble. Since a moment of drawing usually took longer than the time of one utterance, we represented the starting and ending point of the drawing across multiple turns, referring to in the result section, as shown in Turns 76 to 81 in Table 2, drawing continued during six turns in this discourse. Even though this drawing occupied six verbal turns, it does not take six turns but rather one turn. We thus focused on the verbal mode

when a longer drawing turn overlapped with the verbal mode. To show the drawing during these turns in the transcript, we inserted screenshots of the drawing as they occurred in the videos. At times, we also inserted diagrams taken from their worksheets when the video screenshots were not clear or obstructed by the students' bodies.

In addition, we also analyzed students' gesture in their group interactions using McNeil (2005)'s categorization in order to consider its pervasive role in communication and promoting understanding in learning (Crowder, 1996, Kang & Tversky, 2016, Roth, 2001). Given that gestures play a moderate role to link between visual and verbal modes particularly with imagery motion and indicatory action (Kress et al., 2014), we have focused on these two gestures: *Iconic* gestures which resemble some aspects of an object or idea being discussed and *deictic* gestures which direct attention toward an external object or location on the collaborative drawing. While we included iconic and deictic gestures in the transcripts and considered their roles in our interpretation, we did not find it necessary to do a detailed coding on gestures nor show the distribution of gestures for the purpose of this study focusing on the interaction between visual and verbal modes of representation.

In some cases, there was a very small time gap between drawing and talking. To deal with this time gap, the authors agreed that the mode appearing first would take the first turn and the other mode that followed would take the next turn. This method was used for the purpose of this framework, which is to analyze the two modes of interaction.

Through this analytic framework, we observed a basic triad (Plan-Draw-Evaluate) and its variations, which will be explained in the results, within the alternation between the two modes of representation. To maintain the consistency of analysis, we set the boundary conditions of these patterns based on the assumption that these patterns only emerged when all members focused on the same object or concept to represent. This means that if students drew independently, these

patterns did not emerge. The average time duration of one triad observed was 29 seconds. The shortest duration was 7 seconds, while the most prolonged length was 1 minute and 36 seconds.

4. Results

4.1 What interaction pattern emerged between visual and verbal modes? The PDE pattern in group drawing

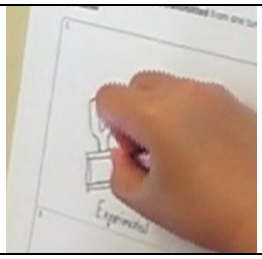
Basic triad: Plan-Draw-Evaluate (PDE) pattern

When students engaged in collaborative discourse with group drawing, there was a recurring Plan-Draw-Evaluate (PDE) pattern in the way visual and verbal modes of representation interacted with each other. This PDE pattern comprised a triad of three basic moves that emerged iteratively in the data and played an essential role in a collaborative drawing. *Plan* involved choosing a direction in what to draw and focusing on what to represent. *Draw* involved constructing what was planned in the previous move with a visual representation. *Evaluate* involved the members who did not draw appraising the drawing. We will illustrate a simple PDE pattern in the example shown in Table 2.

The main question in Lesson 1 was how sound can be transmitted from one tuning fork to another tuning fork through air. Before starting the group drawing activity, the teacher gave some instruction about the experiment, and there was a group verbal discussion to construct an explanation. The example shown in Table 2 started from drawing the second tuning fork after having drawn the first tuning fork on the left side.

Table 2 An example of simple PDE pattern (Group 5, Lesson 1)

Turn	Time	Member			Mode	Move
		G5S1	G5S2	G5S3		
72	1:46:40	And then open up, put the two (*with deictic gesturing to the two tuning forks*), little bit wide.			Verbal	Plan
73	1:46:44			We need to draw the second one.	Verbal	|
74	1:46:45		Yeah.		Verbal	|

75	1:46:46	Like them together *(with deictic gesturing to the first drawn tuning fork*).			Verbal	|
76	1:46:47				Visual	Draw
77	1:46:55		Difficult some out.	|	Verbal	Evaluate
78	1:47:07	That's good enough.		|	Verbal	|
79	1:47:09		Yeah.	|	Verbal	|
80	1:47:16	It just looks like a bag...		|	Verbal	|
81	1:47:20		Yeah, we need to make it professional.		Verbal	|

Note: "|" indicates that the previous drawing or move is continuing.

Plan, the first move in the PDE pattern, began from Turn 72 in Table 2 with G5S1's suggestion about the space between the two tuning forks as he used deictic gesture to point at to the physical tuning forks. G5S3 and G5S2 then agreed to draw the second tuning fork (Turns 73 and 74). G5S1 then suggested that to G5S3 to draw the two together and pointed to the right side of the first tuning fork on the paper in Turn 75 (deictic gesture). These four turns were classified as one plan move. This first move could consist of many utterances by multiple members, as in this case, or one utterance by one member. When there are several utterances as one plan, it is a joint-plan. This plan also involves the use of gestures if needed. In this case, as presented Turn 72 in Table 2, the deictic gesture contributed to direct the participants' attention toward the object in conversation. As presented Turn 75, this deictic gesture played a role to refer the concrete visual information which was the drawn diagram. When there is only one plan move with one utterance, it is a self-plan. In this case, one member both suggests a concept and draws it. Although there are variations, the first move focuses on what to draw and mostly occurs in the verbal mode, as shown.

Draw, the second move of the PDE pattern, began with Turn 76. After hearing G5S1's verbal suggestion, G5S3 drew the second tuning fork to the right of the first one. In this second move,

visual representations were generated to show the object or concept planned in the previous move. The main information and meaning were represented using the visual mode in this move. This move was most often made by one member because two members drawing the same object together was difficult physically and spatially, so it rarely happened. Since students tended to take some time to finish their drawing, the Draw move could continue for many turns when someone in the group began talking. In this case, we marked the emergence of the final move, evaluate, at the start of the verbal utterance even though the drawing continued. This overlapping occurrence between the drawing and evaluate move is shown in the transcript in Table 2. For example, while G5S3 continued to draw from Turn 76 onwards to Turn 81, the evaluate move also began when G5S2 and GS51 started making comments in those turns.

Evaluate, the final move of the PDE pattern, emerged both during and after drawing. Evaluate was carried out by the other members who did not draw and it occurred mostly in the verbal mode. In the example shown in Table 2, G5S1 and G5S2 evaluated G5S3's drawing (Turns 77 to 81). The evaluate move can take place in many ways, such as agreeing, rejecting, elaborating, informing, and negotiating: For example, Turns 77, 78, 79, and 80 were interpreted as agreeing, and informing.

When all group members collaborated together to draw a specific object or concept, the PDE pattern occurred repeatedly. Although the PDE pattern did not always occur when there were students who did not collaborate, this pattern still functions as a basic triad that accounted for the dynamic unfolding of collaborative discourse with group drawing. In this sense, most collaborative discourses can be described through a series of PDE patterns, with a smaller part of the drawing made with each PDE pattern and accumulating to make a complete drawing over multiple PDE patterns. At times, during the dynamic process of collaborative drawing, the PDE pattern does not always consist of a single and linear thread consisting of the three basic triads, but it can also occur in two major variations: interaction chain and overlapping phases.

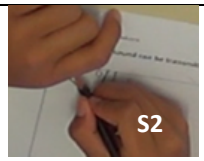
Variations of PDE pattern

Besides the simple PDE pattern described earlier, there were variations of PDE pattern that emerged in our data, notably interaction chains and overlapping between PDE patterns. Interaction chains were cases where students drew the same object or concept in more than three moves. Overlapping PDE patterns were cases where students took two tracks at the same time in their collaborative drawing.

Interaction chains. Interaction chains emerged when students had different ideas about the same object or concept to represent during their discussion. In the process of a discussion, the Draw and Evaluate move emerged many times from the initial Plan move, until one drawing is finalized to present one specific object or concept. An example of an interaction chain in the PDE pattern is the Plan-Draw-Evaluate-Draw-Account-Evaluate (P-D-E-D-A-E) pattern. This variation represents one simple PDE pattern being expanded to involve a response in drawing that emerges after the first evaluate move. In addition, the *Account* move, which is taken by the person drawing, emerges when the person drawing supports their drawing by explaining their intention.

Table 3 An example of an interaction chain as a variation of the PDE pattern (Group 5, Lesson 1)

Turn	Time	Member			Mode	Move
		G5S1	G5S2	G5S3		
110	1:49:01	Yeah, alright, and then you can make it the tiny in the middle.			Verbal	Plan
111	1:49:04			You can now draw…	Verbal	|
112	1:49:06			Do dots, do dots *(with deictic gesturing to the speech bubble).*	Verbal	|
113	1:49:07			 (*drawing tiny dots*)	Visual	Draw
114	1:49:09		No.		Verbal	Evaluate
115	1:49:10		That's not what I am gonna draw.		Verbal	|

116	1:49:12		 (*drawing circles*)	Visual	Draw
117	1:49:20		We need still molecules. And then.	Verbal	Account
118	1:49:30	Just like that still molecules.		Verbal	Evaluate

Note: "|" indicates that the previous drawing or move is continuing.

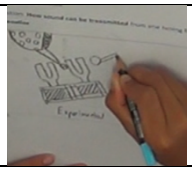
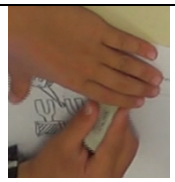
Table 3 illustrates an example of an interaction chain of P-D-E-D-A-E. As mentioned in the basic triad section, group members were asked to represent the process of sound transmission between two tuning forks. At the beginning of the group drawing activity, the members of Group 5 divided a worksheet into four sections to represent the sequential steps of sound transmission. These sections were: (a) before hitting one tuning fork, (b) right after hitting one tuning fork, (c) right after transmitting the sound to the second tuning fork, and (d) the end stage of this sound transmission. The example shown in Table 3 was the first step of the four, so they intended to show that the air particles do not vibrate and planned to zoom in to represent the air particles. In the plan move, G5S3 suggested drawing tiny dots to represent the air particles with deictic gesturing (Turn 112) to arrange the space to draw and then drew the dots (Turn 113, draw move). However, G5S2 rejected G5S3's drawing (Turns 114 and 115, evaluate move) and drew bigger circles to represent the air particles (Turn 116, draw move). After the second draw move, G5S2 informed for his drawing of stationary molecules (Turn 117, account move). G5S2's intention was to clarify this drawing with additional information in a verbal mode. Finally, G5S1 agreed that G5S2's drawing represented the stationary molecules.

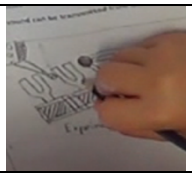
In the evaluate and the draw moves, the drawing of the air particles was more elaborated in terms of the proper size in a zoom-in drawing. This resulted in an interaction chain to assemble different ideas in order to represent a more refined concept. There was an additional account move, which is a move outside of the basic triad. Although the account move emerged as a part of a longer P-D-E-D-A-E pattern, the move also emerged as a part of the P-D-A-E pattern as well.

Outside the basic triad, there are more variations of interaction chains, such as P-D-E-D-E. Through these various interaction chains, students' drawings became more elaborated while still using the PDE pattern as the basic triad.

Overlapping PDE patterns. Overlapping between PDE patterns emerged when students took two different tracks to draw different objects at the same time. In overlapping PDE patterns, there are different drawings drawn by more than one member. This can happen spontaneously in a group drawing activity because group drawing allows students to intervene in the middle of another students' drawing process. The example in Table 4 shows how two PDE patterns can overlap each other. To represent overlapping, an additional column has been added to the original framework.

Table 4 An example of overlapping between PDE patterns (Group 5, Lesson 1)

Turn	Time	Member			Mode	Move	Move'
		G5S1	G5S2	G5S3			
125	1:49:58		And then draw…		Verbal	Plan	
126	1:49:59	Oh, yeah. Draw the mallet *(with iconic gesturing as a motion of drawing mallet with pencil)*.			Verbal	|	
127	1:50:02				Visual	Draw	
128	1:50:06		Oh, let me borrow.		Verbal	Account	
129	1:50:07	 (*erasing the grip of the mallet*)			Visual	Evaluate	
130	1:50:08			Can I draw?	Verbal	Plan	
131	1:50:11	Let me draw it.			Verbal	|	
132	1:50:12				Visual	Draw	
133	1:50:18	|		I want to just to shade them.	Verbal		Plan

134	1:50:19			Visual	Draw	
135	1:50:22	|	I am gonna do shading.	Verbal		Plan
136	1:50:23	Will you shade them to show coming to that state.		Verbal		|
137	1:50:28		Just where is coming from.	Verbal		|
138	1:50:32	Coming from might there *(with deictic gesturing to the space)*.		Verbal		|
139	1:50:33	Cause we strike it from… *(with iconic gesturing as a motion to strike)*		Verbal	Account	
140	1:50:35			Visual		Draw
141	1:50:50	I think you've got shading, cause I like that go to your work.	|	Verbal		Evaluate

Note: "|" indicates that the previous drawing or move is continuing.

There are two drawing tracks shown in Table 4: One focused on drawing and talking about the striking mallet (Turns 130-139) and the other one focused on shading it (Turns 133-141). These two different tracks stemmed from the previous PDE pattern (a P-D-A-E variation) of drawing the mallet (Turns 125-129). In this PDE pattern, G5S2 drew the mallet used as a tool to hit the tuning fork; however, G5S1 erased the drawing. After G5S1 and G5S2 both initiated a self-plan (Turns 130 and 131), G5S1 then proceeded to draw a circle and a long rectangle to represent the mallet and curved lines to represent the movement of the mallet (Turns 132 and 134). This was the first drawing track in this discourse. During his drawing, G5S3 interrupted twice to shade the mallet in order to represent the mallet's movement (Turns 133 and 135). These interruptions were the beginning of the second drawing track. Even though G5S1 had a joint planning with G5S3 about the shading (Turn 136), he still kept his eyes on his drawing of the striking mallet and informed with iconic gesturing as what he drew (Turn 139). His turns here showed that he joined both tracks at the same time. On the other hand, G5S3 shaded the mallet (Turn 140) to represent where the

mallet comes from, as shown in Figure 1, based on the plan move with G5S1. These two tracks—the PDE pattern initiated by G5S1 and the PDE pattern initiated by G5S3—overlapped each other in the group drawing activity. This overlap was spontaneous, because students could individually develop their own ideas and draw them while other members were drawing theirs. The two tracks had slightly different purposes, but the students made more elaborated drawings in terms of the development of their ideas.

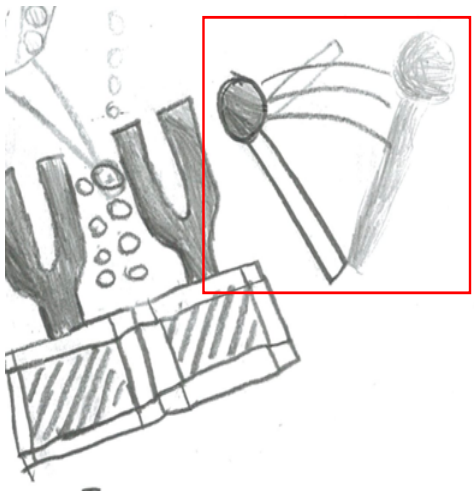


Figure 1 Drawing the mallet and shading (Group 5, Lesson 1)

4.2 How do the verbal and visual modes play complementary roles in the development of ideas through PDE patterns?

Through the alteration between verbal and visual modes in the PDE pattern, this was how the students progressed in the elaboration of their ideas. There is a complementary relationship between the distinctive roles the visual and verbal modes played in alternating with each other. As every alternation emerged through a PDE pattern, students' ideas gradually progressed forward by generating relevant ideas and concretizing, visualizing, and clarifying them. These incremental progressions of ideas constructed through the alternation of the two modes helped students elaborate their drawings by explaining them and negotiate appropriate symbols by conceptualizing what they mean. Students accumulated incremental progressions within PDE patterns and their

variations to complete the whole drawing. These two progressions will be illustrated in the next section.

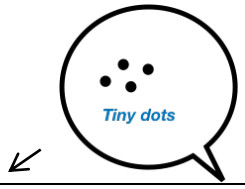
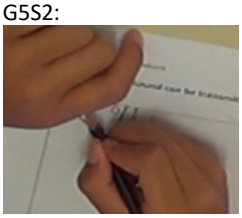
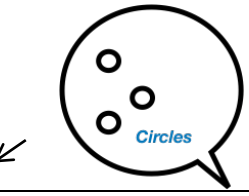
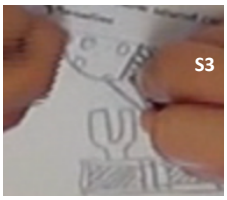
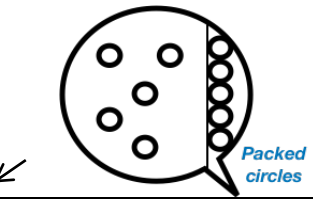
Elaborating drawings

In the alternation between verbal and visual modes of representation, each mode had its own role in a complementary relationship to support group drawing and discourse. As this supportive role, the alternation between the two modes allowed student elaborate their successive drawings. Looking more closely, the plan move focused on what to represent and involved many intentions, such as suggestions, discussions, questions, and requests that surfaced from the verbal talk. The draw move then translated those intentions into a visual form to help visualization and concretely articulate the concept planned in the previous move. In the last move, through the verbal mode, the students negotiated their ideas in order to reach some consensus concerning their drawings with evaluations such as identification, grading, rejection, elaboration, and agreement. Each move played an incremental role in terms of progressing the students' ideas.

An illustration of how this alternation occurred is shown in Table 5. In the table, next to the discursive action (e.g., talk, drawing) for every turn, we included our interpretation of the roles for both the verbal and visual modes in relation to the PDE moves.

Table 5 Elaborating a drawing by the alternation between verbal and visual modes

Turn	Time	Discursive action	Verbal mode	Visual mode	Move
105	1:48:00	G5S3: Don't draw <**them**>. Because the molecules are too small to see. 	*Previous discourse prior to Turn 112*		
112	1:49:06	G5S3: Do dots, do dots *(with deictic gesturing to the speech bubble)*.	Suggesting based on the size of the air particles in the zoom-in section ↘		Plan

113	1:49:07	G5S3: 		Visualizing tiny dots to represent the air particles 	Draw
114	1:49:09	G5S2: No	Rejecting the suggested size		Evaluate
115	1:49:10	G5S2: <**That's**> not what I am gonna draw.	Informing why he rejected the drawing		|
116	1:49:12	G5S2: 		Concretizing the size of circles to represent the air particles with larger circles 	Draw
117	1:49:20	G5S2: We need still molecules. And then.	Informing for the intention of the drawing		Account
118	1:49:30	G5S1: Just like <**that**> still molecules.	Agreeing on the drawing		Evaluate
120	1:49:40	G5S3: I am gonna do to draw the solid molecules.	Suggesting drawing the solid particles of the tuning fork		Plan
121	1:49:42	G5S3: 		Elaborating by drawing packed circles to represent the solid particles of the tuning fork next to the dispersed circles that represent the air particles 	Draw
122	1:49:49	G5S2: I'd like to draw the air particles here *(with deictic gesturing to the space to draw)*, not the solid particles.	Informing the original intention		Evaluate

Note: "< >" indicates tracking of pronouns and underlining indicates tracking of scientific terms or diagrams. "|" indicates that the previous move is continuing.

This example in Table 5 shows that the verbal and visual modes played different roles in facilitating incremental progressions of ideas. As shown in Turns 112 and 113, G5S3 suggested drawing dots and then drew tiny dots to represent the air particles. In this turn, G5S3 did not suggest the exact size of the air particles in verbal mode. The size of the particles was only

visualized when G5S3 drew the tiny dots in visual mode (Turn 113). It is interesting to note that while it is possible to talk about an object without referring to its spatial attributes (e.g., size and shape), it is impossible to draw something without representing its size and shape. This is a good example illustrating the relative affordances between a verbal and visual mode of representation; while the verbal mode is good for representing typological (categorical) meaning, a visual mode is more suited for representing topological (continuous variation; e.g., size, shape) meaning (Lemke, 1999).

As such, after G5S3 revealed the size of the air particles through his drawing, G5S2 realized that dots were not his plan and consequently rejected G5S3's visual representation (Turns 114 and 115). G5S2 then elaborated the size of the air particles by drawing bigger circles without saying anything about their size (Turn 116). In these exchanges, students suggested concepts and rejected drawings through the verbal mode while visualized and elaborated the concept concretely through the visual mode. The chain of meanings in the alternations between visual and verbal modes was also clearly revealed in their use of pronouns. By tracking pronouns in the identification analysis, we found that the pronouns in the verbal mode continuously brought the visual modes into a discursive discourse. For instance, "them" (Turn 105), "that's" (Turn 115), and "that" (Turn 118) were all used by students, sometimes with deictic gesturing, to indicate their current drawings and work with them. Based on the linkages in these alternations, which made use of the relative affordances between the verbal and visual modes within one P-D-E-D-A-E chain, the group's collective idea to represent the air particles in the zoom-in section became more developed compared to the beginning.

The subsequent discourse in the next PDE pattern (Turns 120 to 122) was a progress product that built on the continuous chain of ideas of representing the air particles in the complementary relationship in the alternation between the two modes. Through tracking scientific terms or diagrams in the identification analysis, we found that students' ideas in Group 5 were

incrementally developed in both verbal and visual modes of representation. In the verbal mode, "molecules" (Turn 105), representing just air particles, turned into "still molecules" (Turn 118), illustrating the state of the air particles. Finally, "solid particles" (Turn 121) emerged to represent a tuning fork that can show the context of this phenomenon. On the other hand, in the visual mode, "tiny dots" (Turn 113) were drawn to represent the air particles. This first drawing may not have been the proper size for a zoom-in drawing, but the second drawing, where the air particles were represented with larger circles (Turn 116), was. In the third drawing, "packed circles" (Turn 121) represented the relative distance between particles in solids and gases.

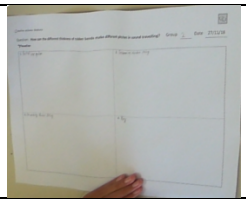
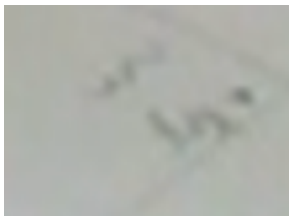
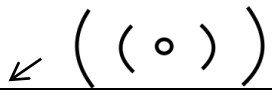
Similar to the earlier discourse, the draw move tapped on the topological affordances of a visual mode as it is not possible to draw numerous particles without also indicating their spatial proximity to one another, while the moves of verbal mode served typological affordances such as describing the state of particles. Since drawings plays a significant role as the main anchor in shaping conceptual dynamic process in collaborative discourse (Parnafes, 2012), the purpose of the alternations between the verbal and visual modes in every PDE pattern was to develop a better representation of the air particles in the zoom-in section. With this shared purpose, each mode emerged alternatively and played a complementary role in constructing the elaborated drawing.

Negotiating symbols

The complementary relationship between the visual and verbal modes was also revealed when students negotiated appropriate symbols to represent several abstract concepts. When students generated drawings to represent their ideas of specific concepts such as vibration or energy, there was often a need to use symbols. Each student, however, had their own preferred symbol to represent a particular concept based on their understanding of the content and the sense of what a good representation was within their classroom (Danish & Enyedy, 2007). The group drawing activity thus involved negotiating among the group members over their individual symbols in order to make a consensus of a joint symbol to represent the features of a particular concept and be

consistent in their use (Prain & Tytler, 2012). The alternations between the visual and verbal modes in PDE patterns facilitated this negotiation.

Table 6 Negotiating symbols by the alternation between verbal and visual modes

Turn	Time	Discursive action	Verbal mode	Visual mode	Move
			*Previous discourse prior to Turn 27*		
27	2:05:48	G2S1: (*After writing each heading of four sections*) Okay.	Informing finishing the heading		Plan
28	2:05:50	G2S2: Vibrations?	Suggesting a key to represent the concept		|
29	2:05:51	G2S1: What should we do for the vibrations?	Requesting ideas		|
30	2:05:53	G2S1: <**This**>?	Suggesting an opinion	↘	|
31	2:05:54	G2S1: 		Visualizing the zigzag lines to represent the vibrations  ↙	Draw
32	2:05:58	G2S3: <**That's**> what I thought as the sound waves.	Rejecting with the drawing of and planning about how to represent the sound waves		Evaluate
33	2:06:01	G2S1: Come on, we can change the sound waves of <**that**>.	Negotiating his own drawing.	↘	|
34	2:06:04	G2S3: 		Concretizing the curved lines to represent the vibrations   ↙	Draw
35	2:06:05	G2S3: We can do <**that**>.	Negotiating one more time		Account
36	2:06:08	G2S2: Do you agree?	Checking with G5S3		Evaluate
37	2:06:11	G2S3: (*With hesitation*) Ah.	Rejecting		|
38	2:06:12	G2S2: Because we let him do *(with deictic gesturing to the G2S3's drawing on eraser)*.	Negotiating with G5S3		|

39	2:06:14	G2S1: <**What**> about the <u>strength of the vibrations</u>?	Suggesting a question about a problem using a related concept.		Plan
40	2:06:16	G2S3: Exactly do with the different lines.	Suggesting how to represent the concept		|
41	2:06:17	G2S1: No way. (*After saying this, G2S1 looked what G2S3 was drawing*)	Rejecting		|
42	2:06:18			Elaborating with <u>many curved lines</u> to represent the strength of the vibrations 	Draw
43	2:06:24	G2S1: But, we can be more worth than show the <u>strength of vib</u>...	Rejecting with the use of a symbol		Evaluate
44	2:06:26	G2S1: We can use <**them**> *(with deictic gesturing to G2S3's drawing on eraser)* for the sound waves. Okay.	Agreeing with the use of the symbol but to its use in another concept		|

Note: "< >" indicates tracking of pronouns and <u>underlining</u> indicates tracking of scientific terms or diagrams. "|" indicates that the previous move is continuing.

As shown in Table 6, the members were negotiating the symbols to be used in the legends of the group drawing. They suggested a concept to be represented and discussed possible symbols in the verbal mode while they presented their visualizations in the visual mode. They may have their preferred symbols for sound waves and vibrations, which are concepts related to sound, because this was the third lesson about sound. Since students needed to represent the different frequencies between thicker and thinner rubber bands, they might have raised the issue of vibrations and sound waves and their strength. The first issue was how to symbolize the concept of vibrations. Through the plan and draw moves (Turns 27-31), the symbol for vibration was suggested. G2S3, however, disagreed with the suggested symbol (Turn 32) and suggested a different idea that she thought was appropriate for the concept of sound waves (Turn 33). After suggesting this, she visualized what she thought on her eraser (Turn 34). However, G2S2 seemed to agree with G2S1's drawing and tried to negotiate about the symbol with G2S3, suggesting using G2S1's drawing in the evaluate move (Turns 36-38). In this discussion, G2S1 raised a new issue

about representing the concept of frequency or magnitude of vibration in the plan move (Turn 39). For this issue, G2S3 also visualized many lines on the eraser based on an elaboration of her previous symbol (Turn 42). Finally, G2S1 agreed on the two symbols that she had visualized not for the vibrations but for the sound waves (Turns 43 and 44). Figure 2 was the result of this discourse that involved both the visual and verbal modes of representation.

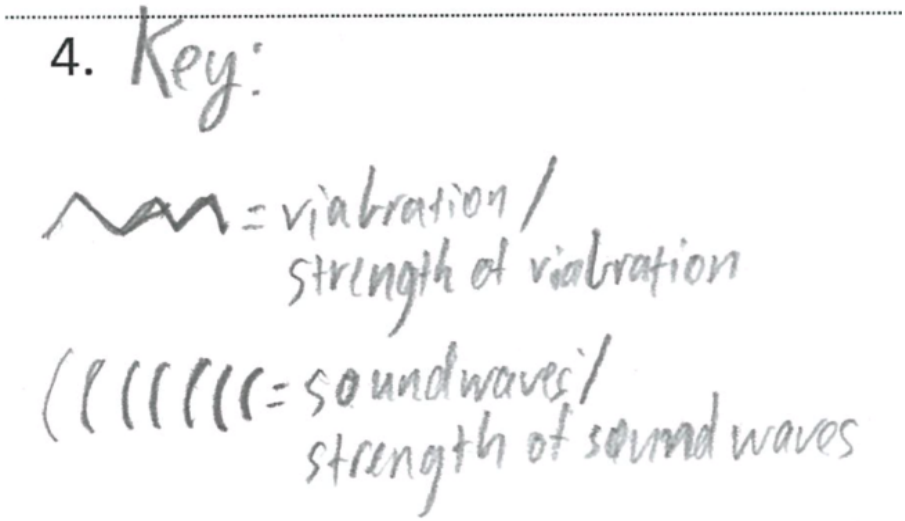


Figure 2 Key of Group 2 in Lesson 3 (First: “vibration/strength of vibration”; second: “sound waves/strength of sound waves”)

The members’ utterances and their three drawings (Turns 31, 34, and 42) showed the development of conceptualization of the related concept in their negotiation. These conceptual progressions of ideas were found in both the visual and verbal modes by tracking scientific terms or diagrams. “Strength of the vibration” (Turn 39) in the verbal mode was determined in relation to the previously suggested relevant concepts, such as the “vibration” (Turns 28 and 29) and “sound waves” (Turns 32 and 33) concepts. Based on these developmental suggestions in the verbal mode, in the visual mode, “zigzag lines” (Turn 31), “curved lines” (Turn 34), and “many curved lines” (Turn 42) were elaborately drawn and considered in making a consensus process. In the alternations between these two modes, as in the previous discourse (Table 5), pronouns such as “this” (Turn

30), “that’s” (Turn 32), and “them” (Turn 43) indicated the drawings that might contribute to retaining the point of negotiation and its development. This development seemed to show that students could elaborate and structure their conceptions verbally within their current external co-constructed visualization (Schwartz, 1995) as well as within their previous shared inscribed symbols (Medina & Suthers, 2013). Thus, it can be interpreted that this conceptualization within the alternation of the two modes make members’ ideas more elaborated and clearer in the same purpose which was to construct the symbols of the related concepts. These distinctive roles formed a complementary relationship in the progression of these ideas.

Indeed, there is a possibility that this negotiation within drawings was interpreted as a modeling activity in the science classroom because this involved key elements of modeling practice (Gilbert & Justi, 2016). If so, we can support students’ collaborative drawing by referring to instructional strategies for teaching modeling. In their negotiation, students created their own symbols to represent the scientific concepts, such as vibrations and sound waves, and modified the shared symbols based on their discussion. They consequently established a coherent conceptual relationship as shown in Figure 2 with the discussed concepts in their incremental progress. It is difficult to see just a drawn diagram in a PDE pattern as a model; however, in the context of a purpose such as constructing a scientific explanation, the accumulated PDE patterns such as this negotiation can be regarded as a modeling practice and their generation can be supported using model-based instructions. For example, guiding students to test and to revise their model in ways that involve correspondence to real data of patterns or scientific phenomena (Passmore, Stewart, & Cartier, 2009) can be an instructional strategy to support them.

5. Discussions

From the analysis at a micro-genetic level, we found and documented the PDE pattern and its variations in students’ collaborative drawing, and illustrated how the pattern was manifested

through a discursive turn-by-turn alternation between visual and verbal modes of representation. In every PDE pattern, each mode of representation played distinct and complementary roles in facilitating the development of students' group drawings. These complementary roles between the visual and verbal modes support previous research on the role of visual representation and drawing (e.g., Ainsworth, 2006; Parnafes, 2012; Van Meter & Garner, 2005). However, our findings reveal a further insight into the dynamic organization and interaction of the modes in relation to the students' collaborative discourse and incremental progression of ideas. In this section, we discuss these findings in terms of the significance of the PDE pattern in coordinating this dynamic organization and interaction as students participated in a collaborative drawing activity of a guided inquiry approach.

5.1 PDE pattern involving interaction between the two modes and incremental progression of ideas

Interaction between the verbal and visual modes: meaning-making within a PDE pattern

The PDE pattern provides a basic social structure not only for the coordination between the verbal and visual modes of representation used by them, but also the collaboration and progression of collective ideas among the group members. Students' collaborative work was negotiated in ways that draw on both the verbal and visual mutual roles, affordances, and complementary relationships. Understanding the mechanism of how these two modes interact is crucial to our understanding of how students collaborate and make meaning in group drawing. A summary and visual explanation of this mechanism within a PDE triadic structure is shown in Figure 3.

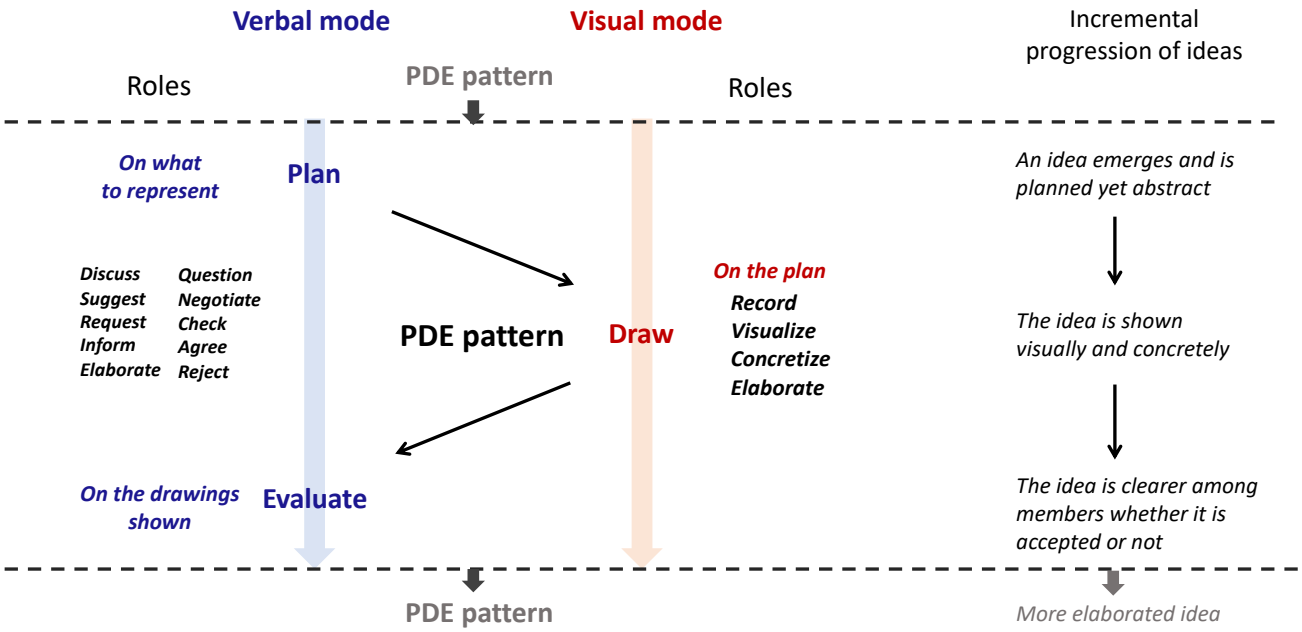


Figure 3 The alternation between the verbal and visual modes in a PDE pattern

As shown in Figure 3, the first move in a PDE triad is a planning on what and how to represent through the verbal mode. In the planning, various discursive functions can emerge such as discussions, suggestions, requests, information, questions, negotiations, checks, agreements, and rejections to determine what should be drawn as a group, with the occasional use of gestures and pronouns to refer to concrete visual information and to focus on a particular object for planning. Although an idea of what to draw emerges and is planned, this idea in its verbal expression is still abstract and could not encompass the full meaning of the concept to be represented (Kress et al., 2014). This is partly because the verbal and visual modes have different affordances in meaning-making (Lemke, 1998). In addition, it is difficult for students to share their visual image in their mind through a verbal mode. Nevertheless, while verbal planning at this stage is still vague and unclear for every member, the plan move is an indication of what a member intends to draw (Van Meter & Garner, 2005) during group drawing.

In the second move, the idea planned in the first move is visualized and concretized. At this stage, the image of the idea is eventually constructed visually and shared to every group member. The shown idea involves additional visual information compared to the previous one with

manifestation of its specificity (Stenning & Oberlander, 1995) and it becomes clearer because group members have now shared the idea through both the verbal and visual modes. Furthermore, in contrast to the verbal mode which is transient, the drawn image is recorded and thus gives more opportunities for group members to elaborate and to articulate their explanations and evaluate their peers' drawing (Parnafes, 2012, Schwartz, 1995).

As the last move in the PDE triad, the shown drawing is evaluated by group members thus allowing the idea to be clarified and sharpened among the members whether it is accepted or not. Group members can discuss and elaborate on the drawing verbally to develop their explanation further while they are seeing and thinking on the visual information created during the draw move. In particular, the last move allowed members to utilize both verbal and visual resources of the suggested and drawn idea simultaneously (Mayer, 2009) so that the shared idea may be clarified and developed further by the group members. Similar to the Plan move, the various discursive functions that can occur are questions, negotiation, agreement, and so on. As a summary of these discursive functions, the meanings of verbal and visual roles have been found in the analysis of this study is shown in Table 7. Further roles of verbal and visual modes can be identified through different settings. Our findings reveal not only how this co-construction of the group's idea occurs through the alternation between the visual and verbal modes of representation, but more importantly, how it is also structured and coordinated within a recurring PDE pattern.

Table 7 Meanings of verbal and visual roles in the PDE pattern

Roles of verbal mode		**Roles of visual mode**	
Discuss	To talk and to argue about what and how to draw	**Record**	To set down in drawing being shared with other members in a stable manner that contribute to manipulating thinking
Suggest	To propose what and how to draw	**Visualize**	To make someone's internal image or abstract ideas visible

Request	To ask other members to suggest and/or to draw ideas	**Concretize**	To name or illustrate specific visual-spatial information that is not revealed by verbal ideas
Inform	To state what and how they represent or to explain what drawings means and its intention	**Elaborate**	To coherently clarify and to sharpen diagrams in relation to other scientific concepts
Elaborate	To expand and to exact conceptual ideas in detail		
Question	To query suggested ideas to others		
Negotiate	To arrange for what and how to draw based on suggested ideas		
Check	To identify confirmation about suggested ideas and/or given questions		
Agree	To consent and to accept suggested and/or represented ideas		
Reject	To refuse to accept suggestions and/or drawn diagrams		

Interaction and its intertextuality: Incremental progression of ideas within and across PDE patterns

The PDE pattern is also crucial in providing a basic unit for the incremental progression of ideas within and across successive PDE patterns, as shown in Figure 3. The alternation between the two modes is how students are able to build on one another's ideas during a group drawing activity. In particular, the incremental progression of ideas can be further understood through the lens of intertextuality. From the perspective of intertextuality (Lemke, 1992), the visualization on paper during the draw move is thus generated as a result of the shared verbal expression from the previous plan move, and conversely from the draw move to the subsequent evaluate move. This chain of plan-draw-evaluate moves allows the collective ideas to be articulated in a public space, thus facilitating its progression within the group. This progression of ideas also continues beyond this PDE pattern to the next progression of more elaborated and refined ideas in the successive PDE pattern. In other words, there are two levels of how the students' ideas progress during group

drawing: a micro-level nested *within* a PDE pattern (alternating between verbal and visual modes) and a larger meso-level *across* successive PDE patterns.

For example, as shown in Table 5, students developed their idea on the size of air particles in the first PDE pattern and they then represented solid particles in the second PDE pattern. The later pattern could be established on the previous collaborative conversation, in which ideas were more clear and articulated, on the size and arrangement of air particles. Likewise, there was also a larger progression of ideas in terms of how the students were representing and thinking about the transmission of sound wave from a tuning fork when we looked across both of these PDE patterns, as well as numerous successive PDE patterns in our analysis (not presented in this paper due to space constraint). Eventually, these successive PDE patterns can be regarded as a co-constructing explanation activity or a modeling practice to being instructionally guided in a mesoscale while a PDE pattern can be understood as a basic sequence to being facilitated the collaboration and idea progressions in a microscale.

5.2 Limitations and Further Utilizations

In this study, we have focused mainly on the PDE patterns, which are a recurring phenomenon of classroom interaction when students cooperatively co-constructed drawings in small groups. We argue that PDE patterns are likely to emerge when there are no over-dominating individuals and all members are motivated to collaborate and engaged in drawing-to-learn. However, these conditions do not ensure the occurrence of PDE pattern if there were insufficient affective and social grounds among group members to make a consensus. These sociocultural conditions are necessary because group work requires some common grounds to be established so that students can make progress in terms of sharing their perspectives and generating joint ideas for development (Edwards & Mercer, 1987; Stahl, 2000). In our study with students in this classroom, we were fortunate that the students were positive learners adaptable for collaborative work.

Furthermore, in terms of multimodality, we have mainly focused on the interaction between verbal speech and drawings from the students in their collaborative drawings, and to a lesser degree for gestures. Gestures play different roles depends on the context of accessible visual resources (Mathayas, Brown, Wallon, & Lindgren, 2019). For instance, articulating a spatial aspect of a science concept without any visual aid may demand more iconic gestures to depict the picturable aspect of the idea (McNeil, 2005). On the other hand, if there are accompanying visual resources, such as an image in a textbook and a physical model, the use of deictic gestures in verbal speech can link the various resources to make intertextual meanings to support students' learning (Kress et al., 2014; Tytler et al., 2020) and focus on a specific object for discussion or explanation (Parnafes, 2012). In this study, there are drawings containing more concrete visual contents that can be easily pointed and guided by gestures to discuss and arrange what and how to represent in a paper. We observed that the role of gestures in collaborative drawings is closer to the latter case than the former one. Given this observation and the main focus of this study, we did not see the need to foreground the roles of gestures in collaborative drawings.

Nevertheless, these limitations in our study do not negate our findings and the purpose of this case study to investigate the process of interaction between the two modes of representations during group drawing. Even when the sociocultural conditions are ideal for collaborative learning, we still do not yet know much about the mechanism of how group drawing occurs, especially when student-generated drawing is still a relatively new pedagogical approach. In our case, as this was the first time the students were engaged in student-generated drawing in a group setting, this provided a unique opportunity for us to learn from the positive examples of how the students engaged in group drawing. We also maintain that the PDE patterns we have revealed are the results of social dynamics and behavior which are independent of the students' academic abilities. As such, the findings from this study are likely to be applicable in general science classrooms. Based on this applicability, there can be more empirical investigations to find further specificities influenced by

cultural elements and to support students where needed. In addition, we also do not have sufficient understanding of the relationship between gestures and drawings in collaborative drawings. Although we have partially analyzed this relationship, we think that there is potential scope to investigate this mechanism further. Future research could adopt the approach in this study to examine collaborative drawing in science classrooms in terms of various sociocultural environments and multimodal resources (e.g., gesture).

6. Implications for Research and Practice

With a growing attention on student-generated representations in science education, we can expect more researchers and teachers to design and enact pedagogical approaches that can empower students to actively construct representations to support their understanding, instead of passively learning from canonical representations. Toward this instructional objective, group drawing is a predominant method for students to discuss their ideas while they draw collectively as a pair or group in traditional classrooms (e.g., Scheiter et al., 2017; Tytler et al., 2020) and computer-supported collaborative learning environments (e.g., Gijlers et al., 2013). The need for group drawing within a lesson's teaching sequence is well accepted by most educators. However, once group drawing begins, few researchers have examined the micro-genetic processes of what goes on within the group work in terms of how the group's ideas developed (or not developed) based on what was said and drawn by individual students. Consequently, students were often left to their own devices during group drawing, with the teacher standing by to intervene in any group when necessary instead of playing a more active role in facilitating or regulating the group discussions and drawings.

Focusing on the discursive details of how group drawing unfolds using a micro-genetic approach, this paper identified a recurring pattern in the coordination between verbal and visual modes along with the progression of ideas planned, drawn, and evaluated by the students in a

group setting. As such, it provides a first insight into the dynamic organization of group drawing that took into consideration simultaneously the (a) multimodal roles and affordances provided by both verbal and visual modes of representation and (b) situated and discursive nature of collaborative discourse. It also reveals the process of group negotiation that involved drawing as a collective objective. From this pattern, we can better understand how primary or secondary school students construct visual representations through group discussions and find possibilities to interpret and to support this construction as a modeling practice. This insight adds a new contribution to previous research that revealed various interaction patterns in classroom talk, notably IRE (Initiate-Response-Evaluate), IRF (Initiate-Response-Follow-up), DGA (Demand-Give-Acknowledge), and TAP (Toulmin's Argument Pattern). The revelation of PDE patterns (which is a form of interaction pattern) extends previous research in classroom discourse that was hitherto constrained to a verbal mode to include also a visual mode at a micro-genetic level. In particular, this study has shown how students structured their collaborative discourse through group drawing involving interactions between verbal and visual modes of representation. We argue that this insight and revelation has the potential to open the field in science classroom discourse, multimodality and student-generated drawings for further research in this area.

Furthermore, the analysis in this study provides an added benefit of aligning the research in multimodality and collaborative discourse. Guided by our theoretical framework and research questions, we have developed and applied an analytical approach that encompassed drawing (a visual mode) in a typically verbal-focused discourse analysis framework. There are two major challenges in integrating non-verbal modes in a turn-by-turn discourse analysis. The first is the difference in timescale between drawing and talking and the second is their spontaneous and simultaneous occurrence among students' discourse. To overcome these challenges, the students' utterances and multimodal actions (captured through video screenshots of their drawing and gesture) are represented horizontally along the same turn in order to show the spontaneous

occurrence and coordination among talking, drawing and gesturing. This analytical approach has the advantage of showing the close connection between multimodal representations (research focus in multimodality) and participants' moment-by-moment actions (research focus in collaborative discourse).

Understanding this interaction involved in group drawing is important in order to better support teachers in promoting student-generated drawing through a guided inquiry approach. While the PDE pattern emerged as a naturalistic observation from a case study, it can be adapted into a prescriptive model to guide teachers in scaffolding the process of group drawing. For example, if a teacher observes that a group of students are not actively collaborating during group drawing, he or she can follow a PDE pattern to support their engagement. This may involve asking students to (a) take turn and suggest what they like to draw, (b) volunteer or nominate someone to draw their suggestion, and then (c) give feedback to what was drawn and come to a consensus on its representation. This process may have to be repeated several times until the teacher or students feel that they have made some progress in their idea development and can be understood as stages of a teaching proposal. If so, this process can allow students to collaboratively participate in their work based on their understanding of how to engage, how to activate their resources, and how to progress in their development (Shim & Kim, 2018). Previous research in documenting the IRE patterns during science classroom discourse (Lemke, 1990) had later paved ways to building more constructivist instructional supports for teachers through IRF patterns, dialogic questioning, and group facilitation (e.g., Chin & Osborne, 2010; Kelly et al., 2000). Likewise, the PDE patterns documented in this study can potentially influence future research to develop instructional strategies to support teachers' enactment of group drawing in order to shape collaborative discourse by students in a guided inquiry, such as using the suggested prescriptive stages.

Past research in student-generated drawing has reported many benefits from this inquiry approach for science learning such as fostering conceptual understanding, reasoning, and

communication (Ainsworth, Prain, & Tytler, 2011). In this inquiry process, group drawing, considering its affordances, is a central activity that enhances the benefits and success of student-generated drawing (Tytler et al., 2020). This paper contributes to our current body of knowledge concerning the mechanism of how collaborative group drawing occurs. It has identified and documented a recurring PDE pattern and its variations that emerged through the interaction between the verbal and visual modes used in group drawing as well as illustrated how students' collective idea progressed incrementally within and across PDE patterns. Based on these findings and discussions, we have gained a better understanding of the interaction patterns involved in collaborative drawings at a micro-genetic level. This understanding has implications in terms of our theoretical knowledge of how students learn from group drawing from a multimodal discourse perspective as well as our practical knowledge of how to support teachers in facilitating group drawing activity within a student-generated drawing approach.

Acknowledgments

This work was supported by Australian Research Council Discovery Project DP180100143 'Drawing science diagrams to enhance students' scientific creativity'. We wish to express our gratitude to David Treagust, Mihye Won, and Felicity McLure who have contributed to this research project.

References

Ainsworth, S. (2006). DeFT: A conceptual framework for considering learning with multiple representations. *Learning and Instruction, 16*(3), 183–198. http://doi.org/10.1016/j.learninstruc.2006.03.001

Ainsworth, S., Prain, V., & Tytler, R. (2011). Drawing to learn in science. *Science, 333*(6046), 1096–1097. https://doi.org/10.1126/science.1204153

Bakhtin, M. M. (1986). *Speech genres and other late essays* (1st ed.). Austin: University of Texas Press.

Blanco-Anaya, P., Justi, R., & Díaz de Bustamante, J. (2017). Challenges and opportunities in analysing students modelling. *International Journal of Science Education, 39*(3), 377-402. https://doi.org/10.1080/09500693.2017.1286408

Brooks, M. (2009). Drawing, visualisation and young children's exploration of "Big Ideas." *International Journal of Science Education, 31*(3), 319–341. https://doi.org/10.1080/09500690802595771

Chandler, P., & Sweller, J. (1996). Cognitive load while learning to use a computer program. *Applied cognitive psychology, 10*(2), 151-170. https://doi.org/10.1002/(SICI)1099-0720(199604)10:2<151::AID-ACP380>3.0.CO;2-U

Chang, H. Y. (2018). Students' representational competence with drawing technology across two domains of science. *Science Education, 102*(5), 1129-1149. https://doi.org/10.1002/sce.21457

Chang, J., Park, J., Tang, K. S., Treagust, D. F., & Won, M. (2020). The features of norms formed in constructing student-generated drawings to explain physics phenomena. *International Journal of Science Education, 42*(8), 1362-1387. https://doi.org/10.1080/09500693.2020.1762138

Chin, C. (2007). Teacher questioning in science classrooms: Approaches that stimulate productive thinking. *Journal of Research in Science Teaching, 44*(6), 815-843. doi:10.1002/tea.2017

Chin, C., & Osborne, J. (2010). Students' questions and discursive interaction: Their impact on argumentation during collaborative group discussions in science. *Journal of Research in Science Teaching, 47*(7), 883-908. https://doi.org/10.1002/tea.20385

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, 9*(4), 902-920. https://doi.org/10.1111/tops.12285

Cromley, J. G., Du, Y. & Dane, A.P. (2020). Drawing-to-Learn: Does meta-analysis show differences between technology-based drawing and paper-and-pencil drawing?. *Journal of Science Education and Technology, 29*, 216–229. https://doi.org/10.1007/s10956-019-09807-6

Crowder, E. M. (1996). Gestures at work in sense-making science talk. *Journal of the Learning Sciences, 5*(3), 173-208. https://doi.org/10.1207/s15327809jls0503_2

Danish, J. A., & Enyedy, N. (2007). Negotiated representational mediators: How young children decide what to include in their science representations. *Science Education, 91*(1), 1-35. https://doi.org/10.1002/sce.20166

Edwards, D., & Mercer, N. (1987). *Common knowledge: The development of understanding in the classroom*. New York: Routledge.

Ehrlén, K. (2008). Drawings as representations of children's conceptions. *International Journal of Science Education, 31*(1), 41–57. https://doi.org/10.1080/09500690701630455

Erduran, S., Simon, S., & Osborne, J. F. (2004). Tapping into argumentation: Developments in the application of Toulmin's argument pattern for studying science discourse. *Science Education, 88*(6), 915–933. https://doi.org/10.1002/sce.20012

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., & Zhang, Q. (2018). Drawing boundary conditions for learning by drawing. *Educational Psychology Review, 30*(3), 1115-1137. https://doi.org/10.1007/s10648-018-9444-8

Garfinkel, H. (1967). *Studies in ethnomethodology*. Englewood Cliffs, NJ: Prentice-Hall.

Gilbert, J. K., & Justi, R. (2016). *Modelling-based teaching in science education (Vol. 9)*. Basel, Switzerland: Springer international publishing.

Gijlers, H., Weinberger, A., van Dijk, A. M., Bollen, L., & van Joolingen, W. (2013). Collaborative drawing on a shared digital canvas in elementary science education: The effects of script and task awareness support. *International Journal of Computer-Supported Collaborative Learning, 8*(4), 427–453. https://doi.org/10.1007/s11412-013-9180-5

Halliday, M. A. K. (1978). *Language as social semiotic: The social interpretation of language and meaning*. London, England: Arnold

Hmelo-Silver, C. E., & Barrows, H. S. (2008). Facilitating collaborative knowledge building. *Cognition and instruction, 26*(1), 48-94. https://doi.org/10.1080/07370000701798495

Horz, H., & Schnotz, W. (2008). Multimedia: How to combine language and visuals. *Language at Work, 3*(4). https://doi.org/10.7146/law.v3i4.6200

Jaipal, K. (2009). Meaning making through multiple modalities in a biology classroom: A multimodal semiotics discourse analysis. *Science Education, 46*(1), 48–72. https://doi.org/10.1002/sce.20359

Kang, S., & Tversky, B. (2016). From hands to minds: Gestures promote understanding. *Cognitive Research: Principles and Implications, 1*(1), 1-15. https://doi.org/10.1186/s41235-016-0004-9

Kawasaki, K., Rupert Herrenkohl, L., & Yeary, S. A. (2004). Theory building and modeling in a sinking and floating unit: A case study of third and fourth grade students' developing epistemologies of science. *International Journal of Science Education, 26*(11), 1299-1324. https://doi.org/10.1080/0950069042000177226

Kelly, G. J., Brown, C., & Crawford, T. (2000). Experiments, contingencies, and curriculum: Providing opportunities for learning through improvisation in science teaching. *Science Education, 84*(5), 624-657. https://doi.org/10.1002/1098-237X(200009)84:5<624::AID-SCE5>3.0.CO;2-S

Knain, E. (2006). Achieving science literacy through transformation of multimodal textual resources. *Science Education, 90*(4), 656-659. https://doi.org/10.1002/sce.20142

Kress, G., Jewitt, C., Ogborn, J., & Charalampos, T. (2014). *Multimodal teaching and learning*. London; New York: Bloomsbury Academic.

Kress, G., & van Leeuwen, T. (2006). *Reading images: The grammar of visual design* (2nd ed.). London: Routledge.

Lehrer, R., & Schauble, L. (2012). Seeding evolutionary thinking by engaging children in modeling its foundations. *Science Education, 96*(4), 701-724. https://doi.org/10.1002/sce.20475

Lemke, J. L. (1990). *Talking science: Language, learning, and values*. Westport: Ablex Publishing Corporation.

Lemke, J. L. (1992). Intertextuality and educational research. *Linguistics and Education, 4*, 257–267. https://doi.org/10.1016/0898-5898(92)90003-F

Lemke, J. L. (1998). Multiplying meaning. In J. R. Martin, J. R. Martin, & R. Veel (Eds.) *Reading science: Critical and functional perspectives on discourses of science* (pp. 87-113). London; New York: Routledge.

Lemke, J. L. (1999). Typological and topological meaning in diagnostic discourse. *Discourse Processes, 27*(2), 173-185. https://doi.org/10.1080/01638539909545057

Maeng, S., & Kim, C. J. (2011). Variations in science teaching modalities and students' pedagogic subject positioning through the discourse register and language code. *Science Education, 95*(3), 431-457. https://doi.org/10.1002/sce.20429

Mathayas, N., Brown, D. E., Wallon, R. C., & Lindgren, R. (2019). Representational gesturing as an epistemic tool for the development of mechanistic explanatory models. *Science Education, 103*(4), 1047-1079. https://doi.org/10.1002/sce.21516

Martin, J. R., & Rose, D. (2007). *Working with discourse: Meaning beyond the clause (2nd Ed.).* London; New York: Continuum.

Mayer, R. E. (1997). Multimedia learning: Are we asking the right questions?. *Educational Psychologist, 32*(1), 1-19. https://doi.org/10.1207/s15326985ep3201_1

Mayer, R. E. (2009). *Multimedia learning* (2nd ed.). Cambridge: Cambridge University Press.

McNeill, D. (2005). *Gesture and thought.* Chicago and London: University of Chicago press.

Medina, R., & Suthers, D. (2013). Inscriptions becoming representations in representational practices. *Journal of the Learning Sciences, 22*(1), 33-69. doi:10.1080/10508406.2012.737390

Mehan, H. (1979). *Learning lessons*. Cambridge, MA: Harvard University Press.

Mercer, N. (2004). Sociocultural discourse analysis: Analysing classroom talk as a social mode of thinking. *Journal of Applied Linguistics, 1*(2), 137–168. 10.1558/japl.v1.i2.137

Merriam, S. B. (1998). *Qualitative research and case study applications in education*. San Francisco: Jossey-Bass Publishers.

Mortimer, E., & Scott, P. (2003). *Meaning making in secondary science classroom*. Maidenhead; Philadelphia: Open University Press.

O'Connor, M. C., & Michaels, S. (1993). Aligning academic task and participation status through revoicing: Analysis of a classroom discourse strategy. *Anthropology & Education Quarterly, 24*(4), 318-335. https://doi.org/10.1525/aeq.1993.24.4.04x0063k

Opfer, J. E., & Siegler, R. S. (2004). Revisiting preschoolers' living things concept: A microgenetic analysis of conceptual change in basic biology. Cognitive psychology, 49(4), 301-332. https://doi.org/10.1016/j.cogpsych.2004.01.002

Park, J., Chang, J., Tang, K. S., Treagust, D. F., & Won, M. (2020). Sequential patterns of students' drawing in constructing scientific explanations: Focusing on the interplay among three levels of pictorial representation. *International Journal of Science Education, 42*(5), 677-702. https://doi.org/10.1080/09500693.2020.1724351

Park, J., & Song, J. (2020). How is intuitive thinking shared and elaborated during small-group problem-solving activities on thermal phenomena?. *Research in Science Education, 50*, 2363–2390. https://doi.org/10.1007/s11165-018-9784-x

Parnafes, O. (2012). Developing explanations and developing understanding: Students explain the phases of the moon using visual representations. *Cognition and Instruction, 30*(4), 359-403. https://doi.org/10.1080/07370008.2012.716885

Parnafes, O., & diSessa A. (2013). Microgenetic learning analysis: A methodology for studying knowledge in transition. Human Development, 56(1), 5-37. https://doi.org/10.1159/000342945

Passmore, C., Stewart, J., & Cartier, J. (2009). Model-based inquiry and school science: creating connections. *School Science and Mathematics, 109*(7), 394-402. https://doi.org/10.1111/j.1949-8594.2009.tb17870.x

Peirce, C. S. (1986). *Writings of Charles S. Peirce: A chronological edition*. Bloomington: Indiana University Press.

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

Prain, V., & Waldrip, B. (2006). An exploratory study of teachers' and students' use of multi-modal representations of concepts in primary science. *International Journal of Science Education, 28*(15), 1843–1866. https://doi.org/10.1080/09500690600718294

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), es2–16. https://doi.org/10.1187/cbe.14-08-0128

Radinsky, J., Oliva, S., & Alamar, K. (2010). Camila, the earth, and the sun: Constructing an idea as shared intellectual property. *Journal of Research in Science Teaching, 47*(6), 619-642. https://doi.org/10.1002/tea.20354

Roth, W. M. (2001). Gestures: Their role in teaching and learning. *Review of Educational Research, 71*(3), 365-392. https://doi.org/10.3102/00346543071003365

Sacks, H., Schegloff, E. A., & Jefferson, G. (1974). A simplest systematics for the organization of turn-taking for conversation. *Language, 50*, 696–735. https://doi.org/10.1016/B978-0-12-623550-0.50008-2

Scheiter, K., Schleinschok, K., & Ainsworth, S. (2017). Why sketching may aid learning from science texts: Contrasting sketching with written explanations. *Topics in Cognitive Science, 9*(4), 866–882. https://doi.org/10.1111/tops.12261

Schnotz, W. (2005). An integrated model of text and picture comprehension. In R. E. Mayer (Ed.), *Cambridge handbook of multimedia learning* (pp. 49–69). Cambridge: Cambridge University Press.

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

Schwarz, C. V., Reiser, B. J., Davis, E. A., Kenyon, L., Achér, A., Fortus, D., Shwartz, Y., Hug, B., & Krajcik, J. (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

Schwartz, D. L. (1995). The emergence of abstract representations in dyad problem solving. *Journal of the Learning Sciences, 4*(3), 321-354. https://doi.org/10.1207/s15327809jls0403_3

Scott, P. H., Mortimer, E. F., & Aguiar, O. G. (2006). The tension between authoritative and dialogic discourse: A fundamental characteristic of meaning making interactions in high school science lessons. *Science Education, 90*(4), 605-631. https://doi.org/10.1002/sce.20131

Shim, S. Y., & Kim, H. B. (2018). Framing negotiation: Dynamics of epistemological and positional framing in small groups during scientific modeling. *Science Education, 102*(1), 128-152. https://doi.org/10.1002/sce.21306

Stahl, G. (2000). A model of collaborative knowledge-building. In B. Fishman & S. O'Connor-Divelbiss (Eds.), *Fourth international conference of the learning sciences* (pp. 70-77). Mahwah, NJ: Erlbaum.

Stake, R. E. (2000). Case studies. In N. Denzin & Y. Lincoln (Eds.), *Handbook of qualitative research* (2nd ed., pp. 435-454). London: Sage.

Stenning, K., & Oberlander, J. (1995). A cognitive theory of graphical and linguistic reasoning: Logic and implementation. *Cognitive Science, 19*(1), 97-140. https://doi.org/10.1016/0364-0213(95)90005-5

Tang, K. S. (2017). Analyzing teachers' use of metadiscourse: The missing element in classroom discourse analysis. *Science Education, 101*(4), 548-583. https://doi.org/10.1002/sce.21275

Tang, K. S. (2020). Discourse strategies for science teaching and learning: Research and practice. New York and London: Routledge.

Tang, K. S., Delgado, C., & Moje, E. B. (2014). An integrative framework for the analysis of multiple and multimodal representations for meaning-making in science education. *Science education, 98*(2), 305-326. https://doi.org/10.1002/sce.21099

Tang, K.S. & Tan, S.C. (2017). Intertextuality and multimodal meanings in high school physics: written and spoken language in computer-supported collaborative student discourse. *Classroom Discourse*, 8(1), 19-35. doi: 10.1080/19463014.2016.1263576

Tang, K. S., Tan, S. C., & Yeo, J. (2011). Students' multimodal construction of the work–energy concept. *International Journal of Science Education, 33*(13), 1775-1804. https://doi.org/10.1080/09500693.2010.508899

Tang, K. S., Won, M., & Treagust, D. (2019). Analytical framework for student-generated drawings. *International Journal of Science Education, 41*(16), 2296-2322. https://doi.org/10.1080/09500693.2019.1672906

Tytler, R., Prain, V., Aranda, G., Ferguson, J., & Gorur, R. (2020). Drawing to reason and learn in science. *Journal of Research in Science Teaching, 57*(2), 209-231. https://doi.org/10.1002/tea.21590

Tytler, R., Prain, V., Hubber, P., & Waldrip, B. (2013). *Constructing representations to learn in science*. Rotterdam, Netherlands: Springer Science & Business Media.

van Dijk, A. M., Gijlers, H., & Weinberger, A. (2014). Scripted collaborative drawing in elementary science education. *Instructional Science, 42*(3), 353–372. https://doi.org/10.1007/s11251-013-9286-1

Van Meter, P., & Firetto, C. M. (2013). Cognitive model of drawing construction. In G. Schraw., M. T. McCrudden., & D. Robinson (Eds.) *Learning through visual displays* (pp. 247-280). Charlotte, N.C.: Information Age Pub.

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 Zee, E., & Minstrell, J. (1997). Using questioning to guide student thinking. *Journal of the Learning Sciences, 6*(2), 227-269. https://doi.org/10.1207/s15327809jls0602_3

Wells, G. (2001). *Dialogic inquiry: Towards a sociocultural practice and theory of education*. Cambridge, England: Cambridge University Press.

White, R., & Gunstone, R. F. (1992). *Probing understanding*. London; New York: Falmer.

Xu, L., Ferguson, J., & Tytler, R. (2020). Student reasoning about the lever principle through multimodal representations: A socio-semiotic approach. *International Journal of Science and Mathematics Education*. https://doi.org/10.1007/s10763-020-10102-9

Yeo, J., & Gilbert, J. K. (2017). The role of representations in students' explanations of four phenomena in physics: Dynamics, thermal physics, electromagnetic induction and superposition. In D. F. Treagust., R. Duit., & Hans. E. Fischer (Eds.), *Multiple representations in physics education* (pp. 255-287). Cham: Springer.

How to cite:
Park, J., Tang, K. S., & Chang, J. Plan-Draw-Evaluate (PDE) pattern in students' collaborative drawing: Interaction between visual and verbal modes of representation. *Science Education*, 1-33.