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# Students' Meaning-Making of Nature of Science: Interaction Between Visual, Verbal, and Written Modes of Representation

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## ABSTRACT

Students' understanding of nature of science (NOS) has been largely examined primarily in written or verbal modes. The visual, verbal, and written modes are essential for students' meaning-making of NOS. However, research has sidelined the interaction among these three modes in understanding students' collaborative discourse of NOS. Informed by theories of multimodality and social semiotics, this paper investigates the interactions between the visual, verbal, and written modes as groups of students engaged in explicit-reflective multimodal representation during NOS instruction. Utilizing a collective case study approach, we planned NOS instruction with teachers, and videotaped how each focal group of students in two grade seven classes in Hong Kong constructed multimodal representations of NOS. Multimodal discourse analysis revealed that the three modes fulfill various purposes during students' co-construction of multimodal representations of NOS. The interaction between the three modes facilitates meaning-making of NOS in four ways: (a) students' re-semiotization of discursive scientific practices into their multimodal ensembles; (b) bridging students' writing of scientific reports to scientists' social certification and dissemination; (c) connecting students' decontextualized meaning-making to contextualized meaning-making of methods and methodological rules; and (d) facilitating students' embodied semiosis in social organizations and interactions of science. Focusing on four episodes of co-constructing multimodal representations of NOS, we illustrate how students' meaning-making of NOS is multimodal in nature and how various modes have their own affordances. We discuss future research directions on how multimodality can facilitate students' meaning-making of NOS.

## 1 | Introduction

In the last few decades, nature of science (NOS) has been an emphasis in curriculum documents across the world as a central component for scientific literacy (American Association for the Advancement of Science [AAAS], 2001; Curriculum Development Council [CDC], 2017; National Research Council, 2012; Ofsted 2021). NOS is defined in the literature as "epistemology and sociology of science, science as a way of knowing, or the values and beliefs inherent to scientific knowledge and its development" (Lederman et al. 2002, p. 498). Students' understanding of NOS has been measured from a cognitive perspective using paper-and-pencil open-ended instruments and follow-up interviews (Khishfe 2019; Peters-Burton, Parrish, and Mulvey 2019) Such understanding has often been identified by pre-existing categories, such as naïve, intermediary and informed (Khishfe and Lederman 2006). Although these studies can measure the effectiveness of a teaching intervention of NOS, the "in-depth" processes (Lederman 2007, p. 869) of how students enacted their NOS understanding in collaborative discourse could have generated more research efforts (see review from Deng et al. 2011).

To explore in-depth meaning-making processes of NOS, students' understanding of NOS can be framed as a kind of *discourse* (Deng et al. 2011). Discourse describes how students of a particular social group deploy language to enact their understanding, which is shaped by sociocultural practices (Gee 2005; Kelly 2011). Discourse is also an epistemic practice by which students construct, evaluate, and legitimize their claims about NOS (Goren and Kaya 2022; Kelly and Licona 2018). In classroom discourse, language co-evolves with other modes of representation to co-ordinate all aspects of meaning-making (Lemke 1998). There has been empirical evidence that students can use various modes to express their NOS understanding, namely the visual mode (Christidou, Bonoti, and Hatzinikita 2021; Finson, 2003; Walls 2012), the written mode (Lederman et al. 2002), and the verbal mode (Yacoubian and BouJaoude 2010). Such evidence suggests that NOS is not communicated by a single mode alone, and thus that any single-mode categorization of students' NOS understanding is incomplete.

Engaging students in composing multimodal representations of NOS could be a potential research approach. This approach also offers pedagogical value since representations of NOS can involve the verbal, visual, and written modes (Erduran and Kaya 2018). Despite emerging efforts in studying how students learn science by drawings, these studies primarily investigated how visual and verbal semiotic modes play complementary roles in the co-construction of drawings (Park, Tang, and Chang 2021; Tytler et al. 2019). There is a lack of studies in characterizing how students coordinate the visual, written, and verbal semiotic modes, particularly, in the context of collaborative discourse. A fine-grained analysis on short episodes could reveal dynamic interactions of students' use of three semiotic modes (Tang, Delgado, and Moje 2014), specifically in teaching and learning of NOS.

The purpose of this paper is to examine the interactions between the verbal, written, and visual modes of representation in students' meaning-making of NOS. The study of students' utilizing of various modes of representation of NOS challenges the notion of dichotomizing students' understanding of NOS into naïve/informed view, as NOS comprises classes of cognitive-epistemic and social-institutional ideas of science that can be negotiated through various semiotic modes (Cheung and Erduran 2023; Erduran and Dagher 2014). As such, past studies in NOS education tend to expect students to attain a particular *written* idea of NOS by the use of paper-and-pencil instruments, neglecting the nuances of NOS understanding situated in different contexts (Dagher and Erduran 2017). Addressing such a critique, multimodal discourse analysis of two seventh-grader focal groups in different Hong Kong classrooms demonstrates the inseparable and distinctive functions of the visual, verbal, and written modes in helping students construct their understanding of NOS. The overarching research question that guides the present study was: *how do students coordinate visual, verbal, and written modes to make meaning of NOS?*

## 2 | Research on NOS Education

In a journal content analysis on research on NOS in the context of scientific inquiry, Khishfe (2022) reported that a large number of these studies used pre- and post-tests to measure the outcome of explicit-reflective instruction of NOS. Although these studies can examine the outcomes of students' understanding of NOS, investigating students' collaborative discourse can also be a fruitful approach to inform teaching and learning of NOS. This section first argues for extending the set of modes through which students' NOS understanding can be examined. A particular framework that inherently includes a range of modes in characterizing NOS itself is the Family Resemblance Approach (FRA) (Erduran and Dagher 2014). Hence, we begin our discussion with a brief review of the FRA to explore how it provides a framework for anchoring students' collaborative multimodal discourse. Subsequently, the section discusses the roles of various modes of representation in students' discourse of NOS.

### 2.1 | FRA to NOS

In school science, NOS refers to learning about science as a "process" that facilitates students to acquire a more critical and realistic view of science (Allchin 2012; Erduran and Dagher 2014). To help students realize the complexity of scientific research (Abd-El-Khalick and Lederman 2000; Allchin 2011), school science may include contemporary perspectives of NOS, for example, the link between science and societies as well as the relationship between epistemological and social-institutional features of science for example by visiting other research groups to learn from their expertise and publishing journal articles (Gandolfi 2020). Some scholars in NOS education have been critiquing the instillation of a simplistic view of science in classrooms (Dagher and Erduran 2017; Hodson and Wong 2017), as students' NOS understanding may potentially vary across contexts and domains (Khishfe 2013, 2017, 2019). Gandolfi (2020), for instance, argued for a "big picture" approach to NOS in science lessons. In her study, students used bubbles, arrows, and written words in mind maps to illustrate the linkage of various NOS aspects in a global history of science intervention (Gandolfi 2020). These mind maps utilize more than one mode, including both the visual and written modes, as arrows and bubbles were considered as a visual mode while words were considered as a written mode. Such work showed that NOS frameworks in school science need to offer macro-categories, enabling students to construct, evaluate, and revise their understanding of NOS through different modes of representation.

Stemming from ideas in the philosophy of language (Wittgenstein 1958), the FRA to NOS stresses that there are similarities and differences in characteristics between different science domains (Irzik and Nola 2011, 2014). Each science discipline is considered as a member of a family, sharing similarities and differences with other members (Irzik and Nola 2014). For example, while all sciences might share the practice of observation, observation in astronomy is different from that in chemistry. In astronomy, an observation of a galaxy would point to a time in the past, amounting to the historical nature of the evidence gathered through observations. In chemistry, an observation may point to a prediction about the products of a chemical reaction being carried out in the present. Students' understanding of such nuances about how different domains of science explicate scientific practices is likely to facilitate their understanding of NOS. Such nuances may be, particularly, important in understanding traditionally problematic topics such as evolution by natural selection where the nature of evidence is often questioned (Gregory 2009).

Drawing on FRA perspective by Irzik and Nola (2011), Erduran and Dagher (2014) further advanced FRA by developing a multimodal wheel that illustrates relationships between NOS categories. This FRA wheel comprises a cognitive-epistemic system and a social-institutional system: a cognitive-epistemic system comprises aims and values, methods and methodological rules, scientific practices, and scientific knowledge; a social-institutional system consists of scientific ethos, social certification and dissemination, professional activities, social values, social organization and interactions, financial systems, political power structures (Erduran and Dagher 2014). Each NOS category can be further visualized using various modes of representation, for example, the nature of scientific practices can be visualized using the benzine ring heuristic which demonstrate the relationships between scientific activities (Erduran and Dagher 2014). Adopting the FRA framework of NOS does not attempt to regulate students' generation of professed *written* statements of NOS, instead valuing students' various resources in meaning-making *within* and *across* NOS categories through discourse. Indeed, a significant feature in Erduran and Dagher's 2014) depiction of scientific practices is the mediating function of discourse in developing explanations. Learners' discourse of these NOS categories can take the form of various modes of representation, such as drawing, writing and verbal discourse (Cheung and Erduran 2023; Erduran et al. 2020).

Four NOS categories from the FRA framework& were chosen to be focus on this study, two categories from the cognitive-epistemic system and the other two categories from the social-institutional system. In the cognitive-epistemic system, *nature of scientific methods and methodological rules*, as well as *nature of scientific practices* were selected because previous empirical work has demonstrated their potential to be represented in the visual and written modes (Erduran and Kaya 2018; Erduran, Dagher, and McDonald 2019). This approach formed a starting point of theorization of how students coordinated different modes in meaning-making of NOS. In the social-institutional system, two NOS categories, namely *social certification and dissemination* and *social organizations and interactions*, were selected because the research team perceived their potential use due to close connections that can be articulated with respect to the nature of scientific methods and methodological rules, as well as nature of scientific practices in the cognitive-epistemic system. The descriptions of each NOS category are explained in the sub-sections below drawing on the book length account of FRA to NOS by Erduran and Dagher (2014).

#### 2.1.1 | Nature of Scientific Methods and Methodological Rules

This NOS category describes diversity of scientific methods and accepted principles that guide scientific investigations. The diversity of scientific methods can be understood by Brandon (1994)'s matrix which states that not all scientific methods involve testing a hypothesis and not all descriptive works involve manipulative experiments. In this matrix, there are four types of scientific methods: (a) manipulative hypothesis-testing involves testing a hypothesis with the use of a manipulative experiment (e.g., testing the effects of light intensity on the rate of growth of plants); (b) manipulative non-hypothesis-testing involves hands-on experiments for measuring parameters without testing a hypothesis (e.g., measuring pH values of chemicals); (c) non-manipulative hypothesis-testing involves study of a hypothesis without doing hands-on experiments (e.g., studying of evolution); (d) non-manipulative non-hypothesis-testing involves a description or measure of parameters (e.g., classifying stones or Mendeleev's prediction of gallium) (Erduran and Dagher 2014). Brandon's matrix has been used as an analytical tool in science education, for example in investigating how examination papers situate scientific methods in chemistry (Cullinane, Erduran, and Wooding 2019). Brandon's framework resonates with the notion of McComas (1996) and Lederman (2004) that there is not a single scientific method. However, its use in science education also extends the discussion about scientific methods by providing a heuristic for expressing specific and different methods beyond a critique of the 'myth' of the scientific method.

Methodological rules involve how theoretical constructs are accepted, changed, or rejected according to a set of accepted principles (Irzik and Nola 2014). For example, in a manipulative hypothesis-testing, learners should be able to explain how hypotheses can be accepted, changed, or rejected and their relationships with different types of variables. The manipulation of an independent variable within a scientific investigation depends on the hypothesis formed in a scientific investigation.

#### 2.1.2 | Nature of Scientific Practices

This category involves learners' reflection on the epistemic basis of scientific practices. As Erduran and Dagher (2014) argued, scientific practices are about asking questions, developing and using models, planning and carrying out investigations, analyzing data, using mathematics, constructing explanations, engaging in argumentation, obtaining and evaluating, and communicating information. This way of framing scientific practices is consistent with educational policies (e.g., National Research Council, 2012, p. 49). The term "nature of scientific practices" was used in this paper instead of "scientific practices" as we emphasized the importance of learners' explicit reflection of how these scientific practices generate, revise, and validate a scientific claim (Berland et al. 2016), instead of equating learners' mere engagement with scientific practices. For example, learners need to explain how a scientific practice listed in the National Research Council (2012) in an inquiry activity can lead to a purposeful generation of scientific claims within the activity.

#### 2.1.3 | Social Certification and Dissemination

This NOS category describes the notion that scientists disseminate and validate their research by doing a range of activities such as presenting their work at conferences and writing manuscripts for peer-reviewed journals (Irzik and Nola 2014). The works of scientists are critically evaluated and reviewed by their peers. This category is similar to the aspect of social dimensions of science in the "shared wisdom" view that scientific knowledge is socially negotiated, specifically the "established values for communication and criticism within social enterprise" such as the double-blinded peer review processes (Summers et al. 2019, p. 1243).

#### 2.1.4 | Social Organizations and Interactions

This NOS category describes that scientific enterprises are socially organized at an institutional level, such as research groups and universities (Erduran and Dagher 2014). For instance, members of a research group visit other research, learning expertise from the other research groups. This NOS category is unique to the FRA framework in terms of describing an important aspect related to social-institutional aspects science in a particular and nuanced manner.

### 2.2 | Explicit-Reflective Collaborative Discourse of NOS

The current study considers discourse of NOS from sociocultural perspectives, rather than viewing NOS as a form of declarative knowledge that can be measured by paper-and-pencil instruments (Ford 2008; Leung 2020). Sociocultural perspectives advance the position that acquiring understanding emerges from social practices and negotiation among people in the world (Lave and Wenger 1991). To help students develop a deeper understanding of NOS, the analytical lens can be switched from coding whole-class questionnaire surveys to delving into how groups of students take part in activities that scientists do in a scientific community, highlighting the importance of "nature of scientists" (Mohan and Kelly 2020). In science classrooms, the discourse of NOS is often implicit (Oliveira et al. 2012) and lacks an acculturation of scientists (Delamont and Atkinson 2001; Delamont, Atkinson, and Parry 2000). Students' understanding of how scientists work (nature of scientists) within the community of practice contributes to their understanding of NOS (Mohan and Kelly 2020).

As there were only a few studies on structurally engaging students in collaborative discourse of NOS (Deng et al. 2011), this study theorizes discourse of NOS as a kind of "explicit-reflective collaborative discourse." In science education literature, explicit reflective instruction was considered an effective teaching strategy to improve students' NOS understanding (Khishfe 2022). Explicit reflective instruction means that instruction of NOS should be intentionally planned and targeted alongside with science content (Khishfe and Abd-El-Khalick 2002). This approach stresses whether students can connect NOS understandings to the targeted science learning activities, and whether they can reflect on these learning activities (Abd-El-Khalick and Lederman 2000). Explicit-reflective instruction involves tasks such as reflective journal writing (Schwartz, Lederman, and Crawford 2004), group discussion (Smith and Scharmann 2006), teacher questioning (Akerson, Cullen, and Hanson 2010), and card sorting (Hansson 2020; Peters-Burton, Parrish, and Mulvey 2019). We coin the term "explicit-reflective collaborative discourse" to refer to intentionally planned opportunities in engaging groups of students to reflect on their NOS understanding in relation to the instructional context. During collaborative discourse, students share and co-construct meaning within the situation at hand as they draw on a variety of resources (e.g., past experiences). "These resources are permeated with specific meaning by past use and have a shaping function on the activity in progress, while at the same time new meanings might emerge and get reshaped over time" (Siry, Ziegler, and Max 2012, p. 313). Contrasting with implicit collaborative discourse, the notion of "explicit-reflective collaborative discourse" accentuates the research and pedagogical values as students collaboratively draw on various resources to make meaning of NOS.

In the context of explicit-reflective approach, students were provided scaffolds to analyze the activities they have participated using a NOS framework, connecting what students have done with those by the scientists, as well as making generalizations about the epistemology of science (Khishfe and Abd-El-Khalick 2002). Similar to the argument on explicit-reflective approach made by Schwartz, Lederman and Crawford (2004), we argue that in "explicit-reflective collaborative discourse," students presented, defended, elaborated, and responded to meaning of ideas in NOS categories within the FRA framework in their own representations, which results in realizing relationships between these ideas within a NOS category and internalizing NOS as an inseparable part of doing science in groups. Specifically, the four NOS categories in the FRA framework are:

- *Nature of scientific methods and methodological rules*: students discuss which type of scientific methods they have been engaging in, such as whether they formed a hypothesis or did a manipulative experiment. Moreover, students can see the logical reasoning that derives the scientific results (Khishfe 2022). As an example, regarding manipulative hypothesis-testing, students can identify how manipulation of different variables is related to forming a hypothesis;
- *Nature of scientific practices*: students reflect on the epistemologies behind scientific practices they have engaged with (Berland et al. 2016), specifically how these scientific practices are interrelated to help generate knowledge claims in relation to the inquiry context;
- *Social certification and dissemination*: students discuss the connections between their works during inquiry activities and the social negotiation activities by the scientists, such as peer reviewing, attending conferences and meetings (Akbayrak and Kaya 2020). For example, students need to communicate methodological details in their scientific reports, such that experiments can be repeated and peer-reviewed by other scientists;
- *Social organizations and interactions*: students reflect on how their scientific activities are socially organized, and connect these socially organized activities to those by the scientists such as scientists at a research center visiting other research center (Akbayrak and Kaya 2020).

### 2.3 | Underemphasis on Multimodality in Collaborative Discourse of NOS

To conclude, research in NOS education seldom theorized "explicit-reflective collaborative discourse," especially in relation to multimodality. More importantly, discourse in common science classrooms involves multiple semiotic modalities, such as texts, graphs, and objects (Airey and Linder 2009; Jaipal 2010; Siry, Ziegler, and Max 2012). As justified previously, representations of NOS can involve the visual, verbal, and written modes. Multimodality, which is a novel lens to examine students' discourse of NOS (Cheung and Erduran 2023), involves the integration of various semiotic modes of representation (Bezemer and Kress 2016; Jewitt, Bezemer, and O'Halloran 2016; Kress 2010). However, previous research studies on NOS education sidelined the role of multimodality in explicit-reflective collaborative discourse. Explicit-reflective collaborative discourse of NOS was often considered by past research studies as involving isolated linguistic modes of representation (e.g., verbal or written) (Sandoval and Reiser 2004). As the theoretical justifications and empirical findings of this paper show, multimodality plays an important role in students' meaning-making of NOS.

## 3 | Research on Multimodality and Social Semiotics

This study draws on theories of multimodality and social semiotics to examine students' explicit-reflective collaborative discourse of NOS. In science education, the area of multimodality tends to investigate the meaning-making process by students' coordination of multiple modes (Kress 2010), such as gestures (Givry and Roth 2006; Roth and Lawless 2002), diagrams (Cheung and Winterbottom 2021; Cheung and Winterbottom 2023; Tang, Won, and Treagust 2019), symbols (Tang, Tan, and Yeo 2010), and tactile (Pun and Cheung 2023; Tang et al. 2022). According to Park, Tang, and Chang (2021, p. 1016), a mode is conceptualized as "a cultural system of resources that people draw upon to make meaning" (also in Bezemer and Kress 2016; Halliday 1978). Various modes mediate human communication and facilitate the process of meaning-making in peer communication (Park, Tang, and Chang 2021). In relation to multimodality, the study of social semiotics focuses on how students create signs within a community through interacting with other people in the world (Bezemer and Kress 2016; Eco 1976). Drawing on both theories, this article carries out the first exploration of how students coordinate visual, verbal, and written modes to create signs of NOS during explicit-reflective collaborative discourse (Sandoval and Reiser 2004).

### 3.1 | Coordination of Visual, Verbal, and Written Modes in Meaning-Making of NOS

The process of multimodal meaning-making can be examined by analyzing students' explicit-reflective collaborative discourse of NOS. A micro-genetic approach allows fine-grained analysis of how students coordinated three modes in meaning-making of NOS on a turn-by-turn basis (Jaipal 2010; Park, Tang, and Chang 2021; Tang 2011). By this analytical approach, the role of each mode in each turn can be unfolded, and researchers can closely examine how the functions of these modes combine in the meaning-making process (Jaipal 2010). Researchers who are interested in the application of multimodality in science education have recently identified functions of various modes. In illustrating the mechanism of sound transmission, the verbal mode plays the roles of discussing, suggesting, requesting, informing, elaborating, questioning, negotiating, checking, rejecting and agreeing, while the visual mode plays the roles of recording, concretizing, visualizing, and elaborating (Park, Tang, and Chang 2021). During the process of model-based reasoning, the visual mode plays the roles of displaying spatial relationships, layering, connecting, and framing; while the verbal mode plays the role of describing the process, suggesting mechanisms and relating drawing to observable phenomena (Sjøberg, Furberg, and Knain 2022). Despite the focus on canonical scientific knowledge or model-based reasoning, such knowledge can inform the present study which examines students' multimodal meaning-making of NOS.

### 3.2 | Multimodal Representations of NOS Create Social Semiotic Spaces

This article offers a novel investigation of how student-generated multimodal representations can act as *social semiotic spaces* (Gee 2005; Wilmes and Siry 2019) where students draw on available resources to represent and communicate meaning of NOS. Social semiotics describes how process of semiosis is influenced by socially and culturally constructed nature of social spaces (Airey and Linder 2009; Bezemer and Kress 2016; Gee 2005). In the semiosis process, students view and produce signs with reference to the signs created in teaching activities and peer interaction (Sensevy et al. 2005). Through this process students can understand a criterial aspect of knowledge under consideration and assimilate it to the current context by drawing on their prior experience (Santini et al. 2022). Semiosis in science classrooms often involves co-deploying and integrating multiple modes of representation or sign systems (Jaipal 2010; Oliveira et al. 2014; Taylor 2019; Violi 2012).

Our study seeks to examine the semiosis process of NOS by engaging students in composing multimodal representations of NOS, which anchors students' explicit-reflective reflective multimodal discourse of NOS (Cullum-Swan and Manning 1994). From multimodal recordings and observations of science lessons, we identified episodes of student-student communication in which multimodal representations were used, and in each episode we analyzed the connected signs that made up chains of meaning-making (Peirce 1931). For example, student-generated representations could facilitate emergent semiosis through interaction (Park, Tang, and Chang 2021; Prain and Tytler 2021; Tang, Delgado, and Moje 2014; Tytler et al. 2019). These representations facilitate *correspondence* between representation and referent, for example the alignment between drawing and physical model (Tytler et al. 2019; Won, Yoon, and Treagust 2014). More importantly, these representations are *multimodal ensembles*, in which various modes contribute to different significance and meaning of the ensemble (Jewitt 2013).

The central notion of the semiosis process is reassigning the meaning of a multimodal ensemble to another through social interaction (Givry and Roth 2006; Jornet and Roth 2015; Wilmes and Siry 2019). In the context of NOS instruction, the semiosis process is often contextualized in history of science, socioscientific issues and scientific inquiry (Khishfe 2022). Collaborative discussion in the context of scientific inquiry could facilitate semiosis of NOS (Oliveira et al. 2012). The rationale of providing students with opportunities for explicit-reflective multimodal discourse in these contexts is to engage students in *re-semiotization* and *embodied semiosis*.

*Re-semiotization* contributes to the resigning of meaning in multimodal ensemble. It concerns how meaning-making changes from one stage to practice, or from one context to another (Iedema 2001, 2016). It is a continuous process in which students have the agency to interact and transform a multimodal ensemble to another, through social, cultural, and historical contextualization (Givry and Roth 2006; Klein and Kirkpatrick 2010; Wilmes and Siry 2019). In our study, teachers use a range of multimodal semiotic resources to make NOS explicit, question students' NOS understanding, and connect NOS to the instructional context. Engaging students in composing multimodal representations provides a social semiotic space for students to re-semiotize their understanding of NOS from teachers' instruction and their embodied experiences (Wilmes and Siry 2019). The process of re-semiotization of NOS is not limited to transforming a two-dimensional multimodal ensemble to another two-dimensional multimodal ensemble. Based on the theory of embodied semiosis (Violi 2012), the co-construction of scientific texts involves the body as a sign, as the body are central to meaning-making (Taylor 2019). In embodied semiosis of NOS, students attend "to moments, persons or materials of interest to a greater of lesser extent, wrapped up in the affective ephemerality of spontaneous interactions" (Taylor 2019, p. 3). Students' explicit-reflective collaborative discourse of NOS can be related to their embodied engagement with inquiry activities.

## 4 | Methods

### 4.1 | Research Design

This paper draws on a collective case study design (Stake 2000) to articulate the research question: *how do students coordinate visual, verbal, and written modes to make meaning of NOS?* The purpose of this collective case study was not to make universal claims that can be generalized to the whole population (Thomas 2021). Instead, it aims to generate deeper insights and inferences (Baxter and Jack 2008; Stake 1995) on the role of different modes (visual, verbal, and written) of representation on students' meaning-making of NOS. The purpose of this study is to provide "thick description" (Denzin 1989) of how different modes interact in the context of meaning-making of NOS. This collective case study involves data from two groups of seventh graders who coordinated different modes to make meaning of NOS.

### 4.2 | Research Context

The multimodal discourse data used in this study were taken from a research project situated in 4 secondary schools in Hong Kong. The aim of this research project was to examine the role of multimodality in facilitating students' meaning-making of NOS, using the NOS framework from Erduran and Dagher (2014). Within these four schools, an international school was investigated in this article. This school is the only school within the sample where students spoke and wrote in one language only (English). The aim of this paper is to highlight the role of multimodality in students' meaning-making of NOS, instead of a combination between multimodal and multilingual resources in facilitating students' meaning-making of NOS.

As justified in the literature review section, the NOS categories of methods and methodological rules, scientific practices, social organizations and interactions, and social certification and dissemination were chosen to be the focus of this study because previous studies demonstrate their meaning-making potential in diverse modes of representation (Erduran et al. 2020). Following the school's curriculum sequence, the researcher (the first author) co-planned lessons with participating teachers on the four NOS categories. At different points in the lessons, students were given opportunities to engage in multimodal explicit-reflective discourse of NOS.

### 4.3 | Research Participants and Selected Cases

The collective case study involves data from two groups of grade seven students (aged 12–13) in different classes who jointly created multimodal representations of NOS. The two different classes, which were taught by the same teacher Raymond. These two groups of students were randomly selected from a pool of students who assented to participate in the study and whose parents consented to take part. Each focal group consists of two male and two female students (see demographic information shown in Table 1). Both groups took part in NOS instruction taught by Raymond (pseudonym). Raymond had been a science teacher for 20 years. He has a bachelor's degree in molecular biology and a master's degree specializing in educational leadership.

### 4.4 | Description of Curriculum Units

In the first stage of developing the curriculum units, two curriculum units in the International Baccalaureate Middle Years Program (IBMYP) were selected to incorporate NOS instruction. This study was situated in two curriculum units, namely "Go Pink!" and "Growing Plants." In the topic of "Go Pink!," students learnt how to classify acids and alkalis according to their properties. They conducted a titration experiment with aqueous sodium hydroxide, comparing the number of moles of acids present in various types of fruit juice. Through these activities, students generated, collected, used software to plot the graphs and analyzed the data. Also, they interpreted the graphs using the concepts of variables and trends.

In the topic of "Growing Plants," students learnt the essential factors for plant growth, such as sunlight and water. They grew their own wheat grass by applying the factors for plant growth. Afterward, they understood crop growth from a social-institutional

**TABLE 1** | Characteristics of lesson sequences in junior science classes in the selected cases.

| | | |
|---|---|---|
| School | Hong Kong International School[a] | |
| Teacher | Raymond | |
| Years of teaching experience | 20 | |
| Class | 7A | 7B |
| Number of students | 25 | 25 |
| Curriculum units | Go Pink, Growing Plants | |
| Number of lessons | 4 | 4 |
| Total lesson hours | 4 h | 4 h |
| Focal group (gender) | 7A07 (M), 7A15 (F), 7A19 (M), 7A20 (F) | 7B01 (M), 7B02 (M), 7B03 (F), 7B04 (F) |

[a]Pseudonym chosen by the authors.

perspective, for example, how social inequality affected hunger and crop growth. In a jigsaw activity, students then researched four factors affecting crop growth, namely desertification, salinity, drought, and nutrient deficiency. They designed their own investigations on their assigned factor affecting crop growth. Students learnt how to manipulate variables through designing their own experiments.

In the second stage of revising the curriculum units, the teacher and the researcher (the first author) had five meetings that span across a semester to discuss where the four NOS categories can be explicitly targeted alongside the curriculum content. These four NOS categories are (1) *nature of scientific methods and methodological rules*, (2) *nature of scientific practices*, (3) *social certification and dissemination*, and (4) *social organizations and interactions*. As justified in Section 2.1, these four categories were targeted as they had some empirical works which provides a starting point for theorizing how students coordinate different modes to make meaning of NOS, as well as ensuring a balance between the cognitive-epistemic and the social-institutional systems (Figure 1 shows a diagram of how different lessons are mapped with the FRA categories). With reference to the teaching and learning plan by Gandolfi (2020), some NOS categories were introduced in both curriculum units, to allow students to revisit the same NOS category in another curriculum unit. In the discussion between the researcher and Raymond, nature of scientific methods and methodological rules, as well as nature of scientific practices are more difficult for students to understand if they were introduced once, hence we decided to reinforce their introduction in both curriculum units.

In the third stage of planning the curriculum units to elicit students' multimodal representations of NOS, the researcher worked with Raymond to introduce the four NOS categories. For example, in lesson 1, Raymond introduced examples of four types of scientific methods. Throughout the lessons, Raymond used guiding questions to prompt students to reflect on the target NOS categories. At the last part of the lesson, Raymond asked students to consider planning, composing, and reflecting on their multimodal representations of NOS. This sequence is adopted from the Plan-Draw-Evaluate pattern from Park, Tang, and Chang (2021). As argued in the literature review section, drawing is not the only kind of semiotic resource that plays an important role in composing students' NOS ideas. More importantly, Raymond suggested that students should reflect on instead of evaluating how their drawing was connected to the instructional contexts. Two criteria were used to prompt students to reflect on their multimodal representations of NOS, whether their representations connected with the content of the lesson, and whether they made full use of different modes to make meaning of NOS. This was also commensurate with the notion of explicit-reflective approach that drawing connections between NOS and instructional was far more important than identifying whether a representation of NOS was correct or not. Therefore, the stage of "drawing" was replaced with "drawing and writing," as well as replacing the stage of "evaluating" with "reflecting." As this study is a collective case study that empirically explores how students coordinated different modes to make meaning of NOS, Raymond did not model how to draw and write NOS ideas for students to follow.

Four 1-h NOS instruction sessions were implemented across the curriculum units of "Go Pink!" and "Growing Plants" (Table 2). The first lesson of the "Go Pink!" unit focuses on developing students' understanding of *nature of scientific methods and methodological rules*. At the beginning of the lesson, students were introduced diversity of scientific methods, which includes the four different types of scientific methods (Brandon 1994). Raymond then prompted students to reflect on whether "Go Pink!" activity and Popoff experiments required either a hypothesis or an experiment using multimodal representations. In the second lesson of the same curriculum unit, the teacher focused on developing student' understanding of *nature of science practices*. The eight scientific practices from National Research Council (2012), such as analyzing data and using mathematics, were explicitly introduced on how they generated knowledge claims. They were then applied these scientific practices to interpret data from the "Go Pink!" activity. At the end of the second lesson, students multimodally reflected on how these scientific practices helped generate knowledge claims in the GoPink activity.

The third NOS lesson, which targeted on *nature of scientific practices* and *social organizations and interactions*, took place at the "Growing Plants" curriculum unit. Raymond explained how scientific practices are related to each other to generate knowledge claims. Students were then engaged in a jigsaw activity. In this activity, students were assigned one expert area on the factor affecting crop growth and researched their area with other students who shared the same "expertise." They then brought back their expertise to the home group and shared their expertise with other students. After that, Raymond then reinforced the idea that scientists often visited other research groups or attended conferences to learn expertise from other scientists. Students then used different modes to reflect on how different scientific practices are linked to each other, as well as what social aspects of science they had learnt with the keyword "research group" given. The fourth lesson targeted on *nature of scientific methods and methodological rules and social certification and dissemination*.

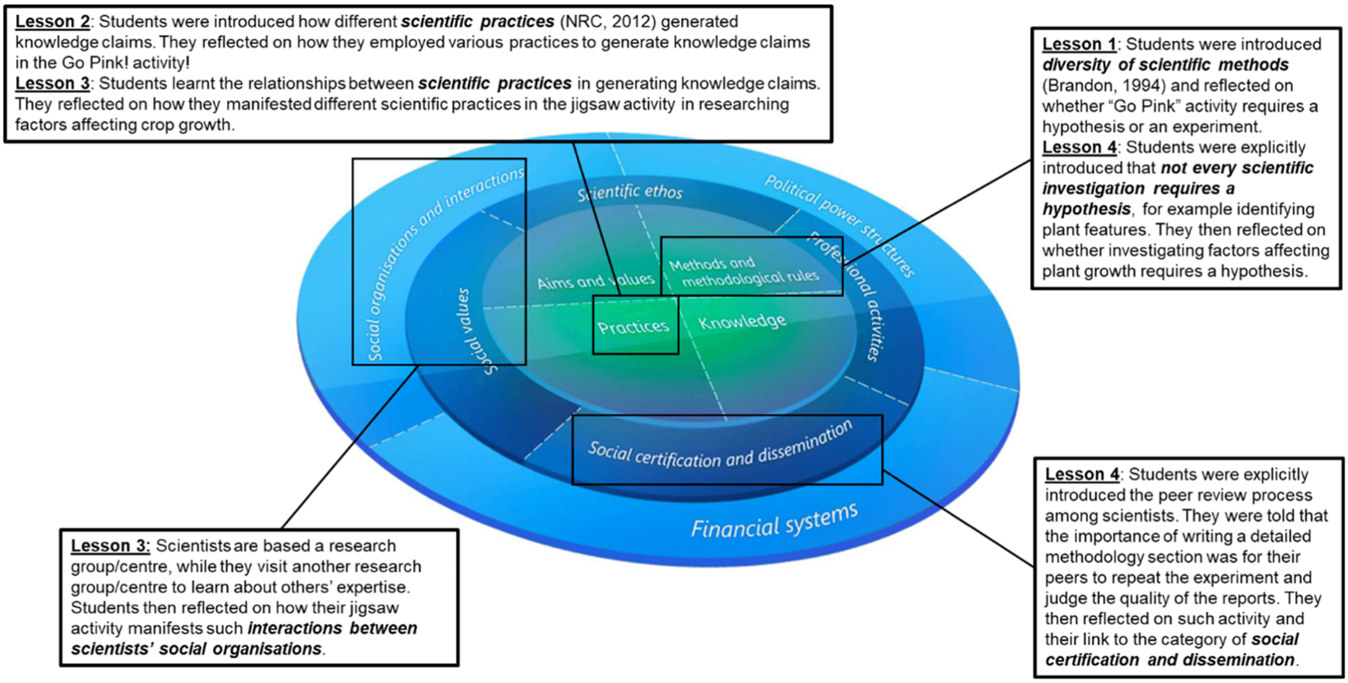



**FIGURE 1** | Diagram showing how lesson content within the two curriculum units align with the FRA categories. The FRA Wheel is from Erduran and Dagher's (2014, p. 28) work.

Students engaged in writing scientific plans to study the factors affecting crop growth before they conducted the actual investigation. To reinforce students' ideas about diversity of scientific methods, Raymond questioned whether both identifying plant features and studying the factor affecting crop growth required a hypothesis. Building on students' responses, he explained to students that depending on the aim of scientific investigation, not every scientific method requires a hypothesis. He also stressed the importance of writing materials and steps clearly in their scientific plans, as scientific reports written by scientists might be replicated by their peers during the peer review process. At the end of the lesson, students were prompted to reflect on their NOS understanding by two questions: "What are the steps of scientific methods? (keywords: hypothesis)," "What are the social aspects of science? (keywords: peer review, replication)."

## 4.5 | Data Collection

All lessons were recorded by three video high-resolution cameras capturing different angles. The first author took part in the lessons as a participant–observer. When students were carrying out explicit-reflective multimodal discourse of NOS, the first author asked students the meanings behind the multimodal texts (Park, Tang, and Chang 2021), but he did not give answers to the questions in the tasks. The main data presented in this manuscript came from the high-resolution camera connected with a microphone capturing the process of students' composing multimodal representations of NOS at the end of the instruction (Figure 2), and the multimodal representations that the focal group students created. As this camera does not tell who is talking, drawing, or writing, this relies on aligning videos with another camera capturing student talk.

## 4.6 | Data Analysis

### 4.6.1 | Preparation of Multimodal Transcripts

The major data source reported in this paper is the video recording of students' collaborative discourse of multimodal representations of NOS. Before carrying out turn-by-turn analysis, we determined what counts as a visual or a written representation by examining the transcripts. A visual representation is defined as drawing arrows, diagrams, symbols (e.g., putting a cross), and lines. We argue that students, especially young learners, can express NOS in both written and visual modes while each mode can complement one another. For example, to demonstrate creative NOS, young learners can draw a figure to show two students adding liquid into a container, which complements their written recall of inquiry experiences (Akerson, Cullen, and Hanson 2010). For the written mode, students wrote down phrases, numbers, and punctuation. To count as a written mode, students did not necessarily write long paragraphs about a complete, elaborated definition of NOS. These phrases can illustrate inquiry contexts, or some ideas within the FRA categories, which can be complemented by other modes. Apart from defining visual and written representations, the verbal representation refers to students' oral utterances.

To conduct discursive analysis, we incorporated the visual and written modes in transcripts adopting a verbal discourse framework. A turn was defined as a moment where a participant spoke, drew, or wrote something. A drawing turn was defined as starting with a pencil landing on a paper to make a scribble and ending with a completion of that scribble (Park, Tang, and Chang 2021); a writing turn was defined as starting with taking down letters and ending with a completion of those letters; a talk turn was defined as starting verbal utterances and

**TABLE 2** | Content and tasks of lesson sequences in Raymond's class.

| Lesson[a] | Lesson sequence | Instructional content | NOS objectives | Prompt for multimodal task |
|---|---|---|---|---|
| 1 | Go Pink (10 h) | • The section covers how to titrate standardized NaOH against weak acid using phenolphthalein as an indicator. | • Students should be able to differentiate different types of scientific methods and to identify whether the type of scientific methods in the inquiry activities they have engaged in (e.g., The GoPink activity is a hypothesis-testing). | • How *scientific method* works in *one* of the following activities: Go Pink/Popoff experiment/or another scientific activity you can think of? Does it involve hypothesis or experiment? |
| 2 | | • Students compared the concentration of acids present in various types of juice. | • Students should be able to reflect on how they utilized different scientific practices to generate knowledge claims in the GoPink investigation. | • What *practices of science* did you have to use? Is there any relationship between these practices of science? (A list of scientific practices provided in PPT) |
| 3 | Growing plants (10 h) | • Students engaged in jigsaw activity on the factor affecting crop growth (salinity, drought, nutrient deficiency) and researched their area other students sharing the same "expertise." <br> • Students learnt about how scientists visited other research groups to learn others' expertise. | • For *nature of scientific practices*, students should be able to reflect on that they communicated their scientific findings as scientists. <br> • For *social organizations and interactions*, students should be able to draw connections between expert/home group to scientists at a research left visiting another research left. | • Reflecting on your experience on the jigsaw task on the consequences of inequality … how are different *scientific practices* linked to each other? (A list of scientific practices provided in PPT) <br> • What social aspects of science did you learn? (keyword: *research group*) |
| 4 | | • Students chose a factor affecting crop growth and designed an investigation by writing clear materials and method sections <br> • The importance of writing the method sections in detail is to allow peer review to assess the quality of reports. | • For *nature of scientific methods and methodological rules*, students should be able to describe how various rules, such as variables, were related to the type of scientific methods. For example, the consideration of an independent variable leads to the generation of hypothesis in a hypothesis-testing investigation. <br> • For *social certification and dissemination*, students should be able to reflect on the importance of writing a succinct methodology section in their reports is related to allowing peer review process among scientists. | • What are the steps of *scientific methods*? (keywords: hypothesis) <br> • What are the social aspects of science? (keywords: *peer review*, *replication*)" |

[a]The duration of each lesson is 1 h.

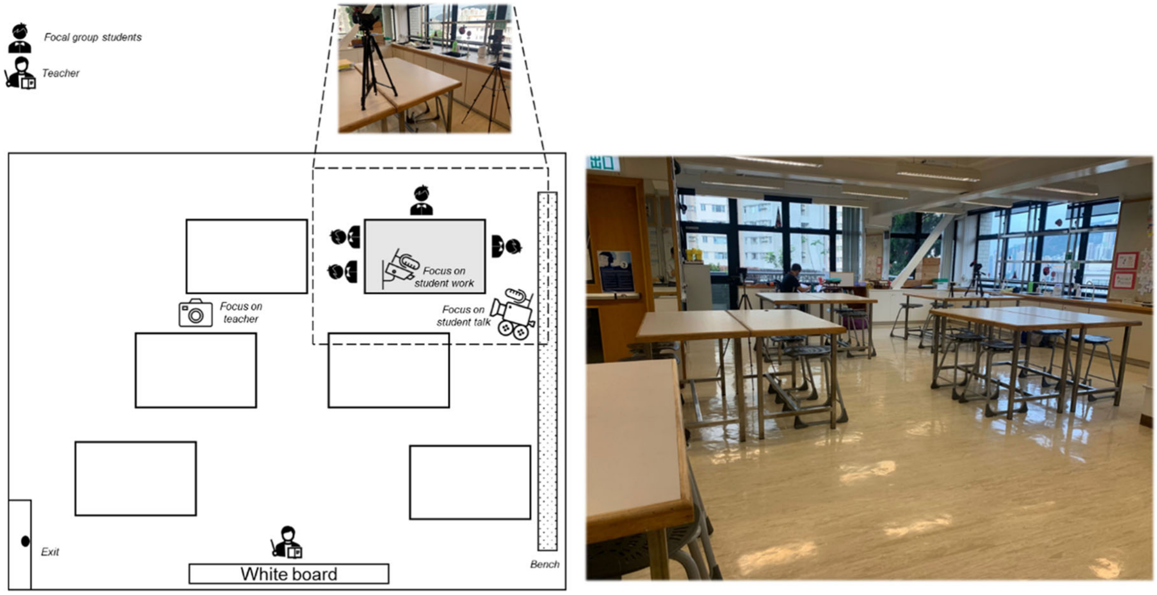



**FIGURE 2** | Classroom plan and positions of camera.

ending with that utterance. As the focus of this study was the interaction between the three modes, there were instances that two modes overlapping with each other. However, if the discursive acts of drawing and writing last for more than one turn in the discourse, they were represented as one turn in the transcript (Park, Tang, and Chang 2021). In the transcript, we also inserted all screenshots of students' actions in writing and drawing as they were shown in a turn documented by the videos (Park, Tang, and Chang 2021). At times, students' drawing and writing were obstructed by their hands, therefore a clear picture was screenshotted from students' artifact and inserted into the analysis of meanings of modes in the transcript. For students' talk, the convention of transcription modified from the study by Sjøberg, Furberg, and Knain (2022) was followed (Supporting Information S1: Appendix 1).

#### 4.6.2 | Analysis Process

The data analysis involved different stages which involve the analysis at a large grain size and longer timescale as well as that of a smaller grain size and shorter timescale (Danielsson et al. 2023; Tang, Delgado, and Moje 2014). First, to interpret students' collaborative multimodal discourse of NOS in relation to instructional context, we documented the teaching purpose, content, approach, and forms of teaching of the lesson episodes by drawing on the taxonomy from Mortimer and Scott (2003).

In the second stage, a micro-genetic approach was used to examine the discursive interaction between visual, verbal, and written modes of representation (Wells 2001). The first author analyzed the functions of each mode in a turn-by-turn manner. Features of visual and verbal modes documented in previous literature (Park, Tang, and Chang 2021) guided the preliminary identification of functions of visual and verbal modes. According to Park, Tang, and Chang (2021), meanings of verbal mode are discussing, suggesting, requesting, informing, elaborating, questioning, negotiating, checking, rejecting, and agreeing, while meanings of visual mode are recording, concretizing, visualizing, and elaborating (Park, Tang, and Chang 2021). To complement the undocumented role of the written mode in student-generated representations in science education literature, its role was identified by constantly comparison method (Merriam 1998). More specifically, the first author extracted notable interaction patterns, documenting features of each mode, and applied these features to each turn in these interaction patterns. This process repeated several times until the list of features of mode can be applied across the interaction patterns. For reliability, the other authors reviewed these patterns together with reference to the context of the lesson and students-generated multimodal representations of NOS.

Following the micro-genetic analysis, we divided the episodes into sections and analyzed which mode was the foregrounding mode in representing students' NOS understanding in each section. In each section, students used certain mode(s) that stand(s) out as important signals to communicate their NOS ideas (Norris 2004). For example, a student might use words to layer down a list of scientific practices in a section of the video, hence the written mode is considered as the foregrounding mode in this section. In the last stage, following an analysis of the interaction patterns, semiotic analysis was conducted on these interaction patterns to understand how students make multimodal meaning of NOS from signs created in instructional contexts (Cullum-Swan and Manning 1994). While a sign of NOS was observed in students' multimodal discourse, the first author traced back teaching materials and episodes, identifying relevant signs that are connected to the NOS representation. He then wrote the description of the process of semiosis of NOS according to concepts such as re-semiotization (Iedema 2001) and embodied semiosis (Taylor 2019). After discussing these interpretations with the other authors, these descriptions of semiosis process have been refined through iterative rounds of email communication, online collaboration, and meetings with all authors.

## 5 | Results

As mentioned above, we investigated how two focal groups in Classes 7A and 7B carried out multimodal meaning-making of

NOS. Four major themes were identified in the analysis: multimodality (a) facilitates a re-semiotization of discursive scientific practices into their multimodal ensembles (episode 1); (b) bridging students' work to scientists' social certification and dissemination (episode 2); (c) opens a semiotic space for bridging decontextualized meaning-making to contextualized meaning-making of methods and methodological rules (episode 3); and (d) facilitates embodied semiosis in social-institutional aspects of science (episode 4) (see Supporting Information S1: Appendix S2–S5 for full transcript).

## 5.1 | Episode 1: Representing Nature of Scientific Practices in the Go Pink! Activity

This episode was taken from Class 7A focal group's discussion of nature of scientific practices in lesson 2. At the beginning of the lesson, Raymond explained the meaning of eight scientific practices (National Research Council, 2012) grounded in the FRA framework. After introducing the eight scientific practices, Raymond engaged students in drawing bar charts to document experimental results in Go Pink activity. In the Go Pink activity, students found out the volume of alkali needed to turn a mixture of different types of juices and phenolphthalein from colorless to pink. After the students plotted the graph, they were involved in constructing explanations regarding the acidity of each type of juice. When Raymond guided the process of constructing explanations, he asked students to reflect on what and how scientific practices were applied in interpreting the graph from Go Pink activity. At the end of the lesson, students were asked to use the drawn and written modes to reflect on what practices of science they have used and the relationships between these scientific practices.

The process of composing the multimodal representation shown in Figure 3 was documented in Table 3. The conversation began with linguistic modes (written and verbal) which focused on discursive scientific practices used in Go Pink activity including "analyzing data." Student 7A07 suggested "I think we have to use 'analyze data'" (Turn 1) while Student 7A19 suggested that three scientific practices, "ask questions," "carry out investigation," and "analyze data," were involved in Go Pink inquiry activity (Turn 2). After documenting "analyze data" on the A3 paper, Student 7A07 questioned whether they carried out the investigation (Turn 4) and Student 7A19 questioned whether they asked a question (Turn 5). The scientific practice raised by Student 7A19 and was then agreed by Student 7A15, and then Student 7A15 wrote it on the paper (Turn 6) as well as her thought "construct explanation" (Turn 7).

From Turns 18 to 41, the focal group students extended their discussion from linguistic modes to the visual mode. Drawing of a bar chart became a foregrounding mode (Kress et al. 2001) in these turns which mediated students' discussion of the scientific practice of "construct explanations." The bar chart indicates different levels of juice volume required to neutralize alkali. Particularly, the bar representing the volume of alkali required to neutralize acid present in grape juice was darkened, indicating its higher pH value. The various levels of volume of alkali required to neutralize the acid present in fruit juice enabled students to make meaning of the written scientific practice "construct explanations." The visual mode illustrates the "Go Pink!" inquiry activities which supports students' further meaning-making of how scientific practices contribute to generation of knowledge claims regarding the comparison of various concentrations of acids in different types of juice in Turns 43–46.

Between Turns 43 and 46 (Table 4), the alternation between the verbal and written modes facilitated students' meaning-making of nature of scientific practices. At this point, students did not only recall what they did in the "Go Pink!" activity, instead they elaborated how they made use of scientific practices to generate knowledge claims. An indexical line was extended from "construct explanations" (Turn 43). Following that, Student 7A15 expanded the idea by writing "we constructed explanations and carry out them and compare them" (Turn 44) related to thematic role of "construct explanation." Similarly, Student 7A15 drew an indexical line to extend the scientific practice "Analyze data" and justify how it helps generate knowledge claims by writing "we had to analyze the data to get the information we gathered" (Turn 46). In terms of meaning-making of *nature of scientific practices*, comparing data of different juices and gathering information was considered as evaluating the evidence provided in the bar chart. Then, they constructed an explanation regarding acidity of different juices as indicated in

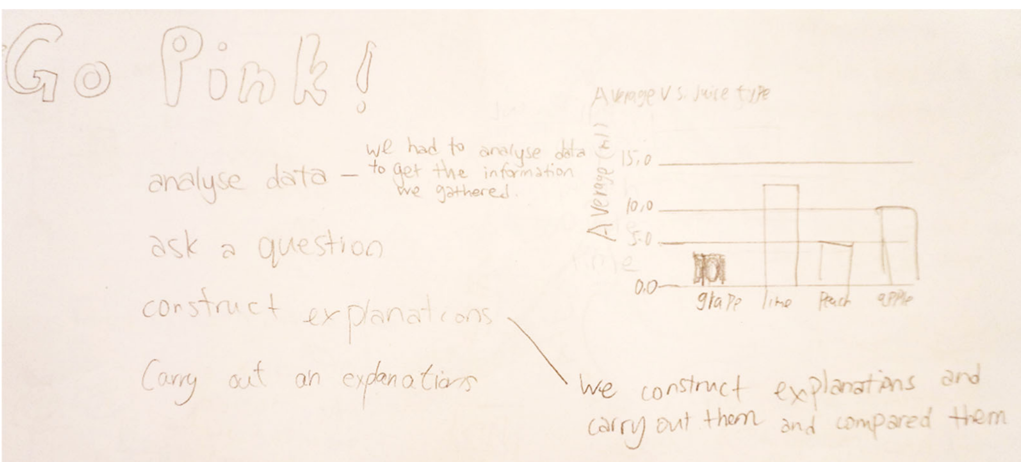
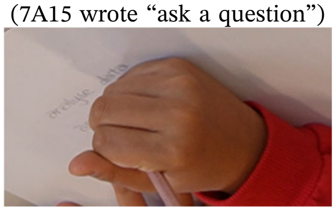
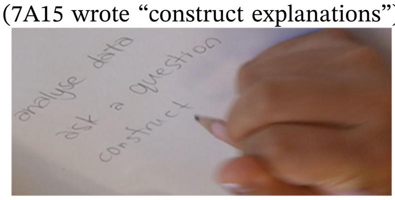



**FIGURE 3** | The representation of nature of scientific practices by Class 7A focal group students.

TABLE 3 | Episode 1: layering down individual scientific practices.

| Turns | Time | Verbal utterances (with screen capturing of writing and drawing processes) |
|---|---|---|
| 1 | 01:02:12 | 7A07: I think we have to use analyze data. |
| 2 | 01:02:15 | 7A19: We did ask questions. We carry out investigation. We analyze data. |
| 3 | 01:02:22 | 7A20: We analyze data. Right? Analyze data... (7A20 wrote "analyze data")  |
| 4 | 01:02:48 | 7A07: So we carried out an investigation? |
| 5 | 01:02:51 | 7A19: Ask a question? |
| 6 | 01:02:52 | (7A15 wrote "ask a question")  |
| 7 | 01:03:06 | (7A15 wrote "construct explanations")   |

the bar chart. Students started to consider the relationships among scientific practices.

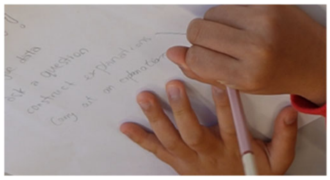
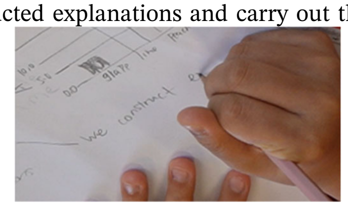
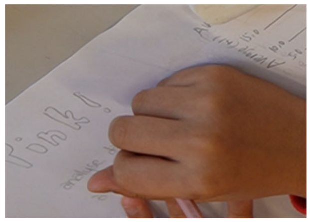
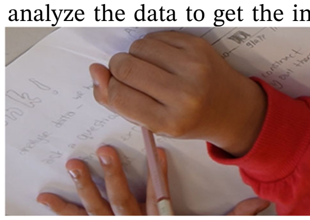
From a semiotic perspective, students *re-semiotized* discursive scientific practices into a *multimodal ensemble*. The process of *re-semiotization* delineates the shift of meanings across different modes when meaning-making resources were moved from one social context to another (Bezemer and Kress 2008). Individual scientific practices were presented to students, while these scientific practices were not grounded in a specific context of explicit NOS instruction. However, students initially engaged in linguistic representations of scientific practice, while drawing of a bar chart showing average volume of alkali required to titrated against different types of juice bridged their understanding of the nature of scientific practices from decontextualized context to the context of Go Pink! Activity. Students acquired semiotic resources at hand, and put them in contextualized meaning-making (Prior and Hengst 2010). The construction of bar chart led to an expansion of meaning of "analyze data" and "construct explanations." They elaborated "analyze data" by explaining "to get the information we gathered," as well as extended the meaning "construct explanations" by writing "carry out them and compared them." These expanded meanings were also coherent with visual indication of different volume of alkali required to titrate against various types of juice. The drawing of the bar chart summarized the kind of data in the "Go Pink!" activity, while linguistic representations explained mental and material processes behind each scientific practice. Hence, the combination of and interaction between different modes was considered as an *multimodal ensemble* (Jewitt 2013).

## 5.2 | Episode 2: Representing Social Certification and Dissemination in Writing Scientific Reports in Growing Plants

This episode was taken from Class 7B focal group's discussion of social certification and dissemination in lesson 4. In the lesson, before students began to investigate different factors affecting crop growth, Raymond told them to write a clear and detailed methodological section. Raymond has carried out explicit-reflective teaching on the NOS category, social certification, and dissemination. He explained to the students that writing a detailed methodology section for their scientific reports was important for other peer reviewers to assess their quality of research, as well as replicating the experiment. Also, he cited some examples of well-known journals such as *Science*, as a venue for publication of scientific research. At the end of the lesson, students were asked to reflect on social certification and dissemination.

The process of students' composition of multimodal representations of social certification and dissemination was documented in Table 5. This episode began by student 7B02 who used the written mode to recount their experience of writing a

**TABLE 4** | Episode 1: Expanding linguistic meaning of nature of scientific practices.

| Turns | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 43 | 01:08:25 | (7A15 drew an indexical line to connect “Construct explanations”)  |
| 44 | 01:08:27 | (7A15 wrote “we constructed explanations and carry out them and compare them”)  |
| 45 | 01:10:02 | (7A15 drew an indexical line to connect “Analyze data”)  |
| 46 | 01:10:05 | (7A15 wrote “we had to analyze the data to get the information we gathered”)  |

clear and detailed material list (Turn 1). After recounting their experience using the written mode, student 7B01 used the written mode to bridge their experience to scientists' professional works by layering down “We learnt how scientists can communicate and all the things that need to happen to publish scientific data” (Turn 2), followed by 7B04's visualization of materiality of a clipboard (Turn 3). In Turn 4, 7B01 verbally suggested the representation of communicating scientific findings in the journal. After drawing a clipboard, students discussed the identity of clipboard (Turns 5–6).

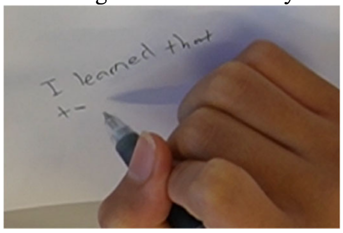
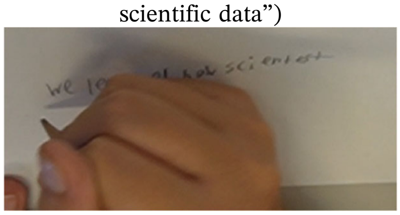
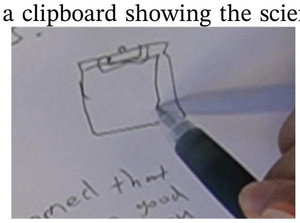
As revealed in the above episode, the written mode was the foregrounding mode for students' representations of social certification and dissemination, while the visual mode supported their written representation. In terms of semiotic analysis, students initially recounted their own experiences using the first-person pronoun “we” and the third-person pronoun “scientists” (turn 2) who were involved in the publication and dissemination process. Acculturation of scientists (Delamont and Atkinson 2001; Delamont, Atkinson, and Parry 2000) is important for students to develop a more informed understanding of NOS. As seen in this episode, the inclusion of both first-person and third-person views demonstrated that they bridged their works related to social certification and dissemination to those by the scientists.

### 5.3 | Episode 3: Representing Methods and Methodological Rules in the Topic of Growing Plant

This episode was taken from lesson 4 in Class 7A when Raymond introduced diversity of scientific method and methodological rules to his students. To begin with, Raymond recalled the types of variables that need to be considered in a fair test. Raymond also questioned students whether every scientific investigation requires a hypothesis, for example, identifying plant features and putting plants into groups (Figure 4). The researcher and Raymond discussed Brandon (1994)'s theory, agreeing that an explanation of when and why scientific investigation requires a hypothesis prompts students to understand the principle of scientific investigation of factors affecting crop growth.

In this episode (Table 6), student 7A20 wrote “Independent variable” (Turn 1) on the A3 paper. This was then followed by her writing of ‘Dependent variable” (Turn 2) below “Independent variable.” Later, to figure out if every scientific investigation needs a hypothesis, Student 7A15 wondered if formulating an independent variable requires a hypothesis and asked, “this one needs a hypothesis, right?” while using her pencil to point at the written text “independent variable” (Turn 5). She was also not sure about

**TABLE 5** | Episode 2: Representing social certification and dissemination.

| Turn | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 1 | 01:01:30 | 7B02: I learnt that make a good material list you have to consider everything. (7B02 wrote "I learnt that to make a good material list you have to consider everything")   |
| 2 | 01:01:42 | (7B01 wrote "We learned how scientist can communicate and all the things that need to happen to publish scientific data")  |
| 3 | 01:02:43 | (7B04 drew a clipboard showing the scientific report)  |
| 4 | 01:02:49 | 7B01: Like communicating information (.) the journal one. |
| 5 | 01:02:54 | 7B02: It is a clipboard. |
| 6 | 01:02:55 | 7B03: Oh! It is a clipboard! |

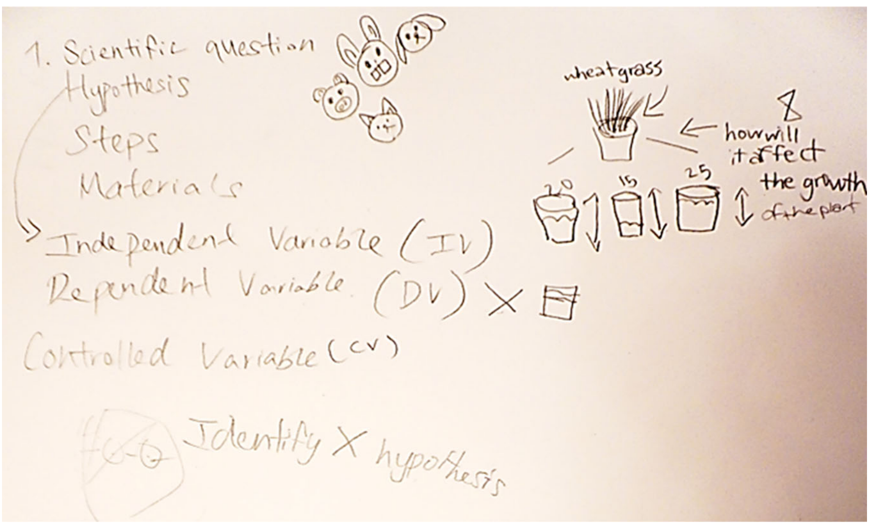
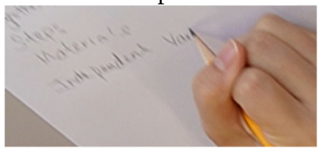
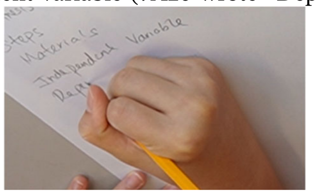
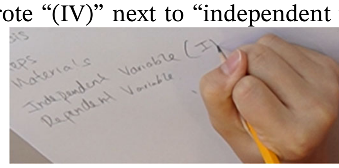
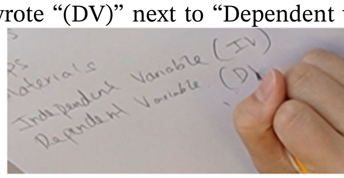
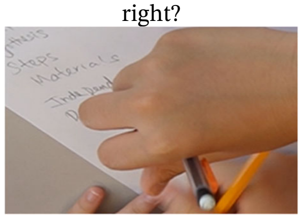
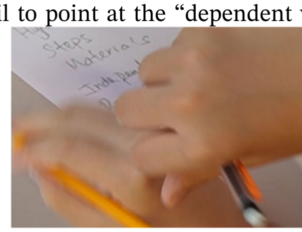
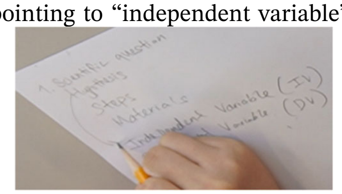
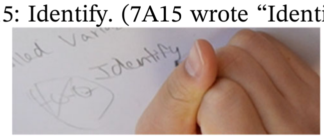



**FIGURE 4** | The representation of methodological rules and diversity of scientific methods by Class 7A focal group students.

whether dependent variables require a hypothesis. Therefore, she checked with 7A20 by asking "this one doesn't need?" and pointing at the written "dependent variable" (Turn 6). Student 7A20 did not reply and drew an arrow to point the written "Hypothesis" to "Independent variable (IV)" (Turn 7), showing that hypothesis is the basis of an independent variable.

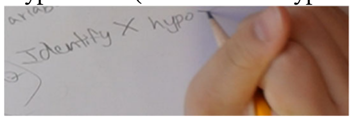
After writing the names of variables, students began to visualize the materiality of scientific investigation (Turns 10–23). Student 7A15 drew three plant pots with different levels of water. Such drawing extended the meaning of the written types of variables, while justifying how students manipulated variables regarding different volumes of water on the crop growth. Apart from addressing methodological rules, when the teacher asked the

**TABLE 6** | Episode 3: Representing nature of scientific methods and methodological rules.

| Turn | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 1 | 00:00:45 | 7A20: Independent variable. (7A20 wrote "independent variable.")  |
| 2 | 00:00:55 | 7A20: And dependent variable (7A20 wrote "Dependent variable.")  |
| 3 | 00:01:00 | (7A20 wrote "(IV)" next to "independent variable.")  |
| 4 | 00:01:02 | (7A20 wrote "(DV)" next to "Dependent variable.)  |
| 5 | 00:01:05 | 7A15: (use her mechanical pencil to point at the "independent variable) this one needs a hypothesis, right?  |
| 6 | 00:01:09 | 7A15: (use her mechanical pencil to point at the "dependent variable") this one does not need?  |
| 7 | 00:01:10 | (7A20 drew a curved arrow connecting "hypothesis" and "independent variable" with the arrowhead pointing to "independent variable")  |
| 24 | 00:03:02 | T: Is there any investigation that doesn't require a hypothesis? |
| 25 | 00:03:03 | 7A15: Identify. (7A15 wrote "Identify".)  |

(Continues)

**TABLE 6** | (Continued)

| Turn | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 26 | 00:03:09 | (7A15 drew a cross next to "Identify".)   |
| 27 | 00:03:13 | 7A15: Hypothesis. (7A15 wrote "hypothesis".)   |

students whether there is an investigation not requiring a hypothesis (Turn 24), student 7A15 recalled that the activity of identifying does not require a hypothesis. She then wrote "Identify" (Turn 25), drew a cross next to "Identify" (Turn 26) and wrote the word "hypothesis" (Turn 27) next to the cross.

In this episode, analyzing students' alternating between the verbal, visual, and written modes traced their micro-development of understanding of nature of scientific methods and methodological roles. As drawing a curved directional arrow from "hypothesis" to "Independent variable" is a more apt form (Kress et al. 2001) than writing to illustrate the relationship between hypothesis and independent variable, student 7A20 chose to use a directional arrow to indicate the dependence of independent variable on hypothesis. Another example was that at the end of the episode, student 7A15 put a cross between the written words "Identify" and "Hypothesis." Drawing of a symbol and writing of NOS discrete terminologies helped making meaning of hypernymy–hyponymy relation that identifying plant features is a kind of non-hypothesis-testing scientific investigation. In terms of semantics, hypernym is a supertype or an umbrella term while hyponym is a more specific subtype of hypernym (Brinton 2000).

Drawing can open a semiotic space for bridging decontextualized meaning-making to contextualized meaning-making of methods and methodological rules. Writing is the foregrounding mode at the beginning (Turns 1–7), then drawing (Turns 10–23), and then back to writing (Turns 24–27). At the beginning, naming of various types of variables was not initially embedded in a particular inquiry context (Turns 1–7). Following the writing of various types of variables, visualization of materiality of apparatuses contextualized students' understanding of methodological rules within their own investigation that study factors affecting crop growth. The visual mode illustrated how variables were manifested in the context of this investigation, and their realization of the relations between independent variable and hypothesis.

### 5.4 | Episode 4: Representing Social Organizations and Interactions After Jigsaw Activity

This episode was taken from lesson 3 in Class 7B when Raymond introduced social organizations and interactions to his students. In this lesson episode, Raymond had designed a jigsaw task to teach the NOS category of social organizations and interactions. Students were assigned a role in researching how different factors affect global crop growth, drought, salinity, and nutrient deficiency (Figure 5). Students were assigned the same factor came together to form an expert group, discussing how the factor affects global crop growth. Afterward, they brought back their expertise and shared it with members of the home group. Aspects of social organization and interactions, such as scientists attending conferences to learn expertise from other groups and visiting other research groups to learn their expertise, were explicitly mentioned before the task of constructing multimodal representations of NOS. At the end of the lesson, students were given opportunities to co-construct a multimodal representation that illustrates their understandings of social-institutional aspects of science after they have engaged in the jigsaw task.

This episode (Table 7) shows how the focal group of students in Raymond's class negotiated the aspect of social organizations and interactions, with the aid of visual, verbal, and written modes of representation. At the beginning of the episode, 7B01 requested 7B03 to draw how they talked science (Turn 1), followed by 7B03 drawing two matchstick individuals (Turns 2 and 3). This was then agreed by both 7B01 and 7B03 (Turns 4 and 5). In Turns 6 and 7, three vectors were drawn in front of the mouth of the matchstick individuals, showing verbal processes of how students themselves talked science. Lines extending from the matchstick individual were drawn to concretize the relation between scientists and their speech (Turns 8, 10, and 13), coupled with written sentences "I like science" (Turn 9), "I think this happens because…" (Turn 11) and "Well I think it happens because…" (Turn 14). These written speech of "matchstick" individuals resonated with their embodied enactment as they also spoke in a sentence structure "I think … because…" when they brought back their expertise to their home group (as indicated in Figure 5). Interaction between the visual, verbal, and written modes helped them communicate embodied experience in social organizations and interactions.

Right after they composed the multimodal representation of how they talked, they began to visualize the scientific context (Table 8). In turn 16, a student wrote about the importance of communication as a social aspect of science. The signs made by

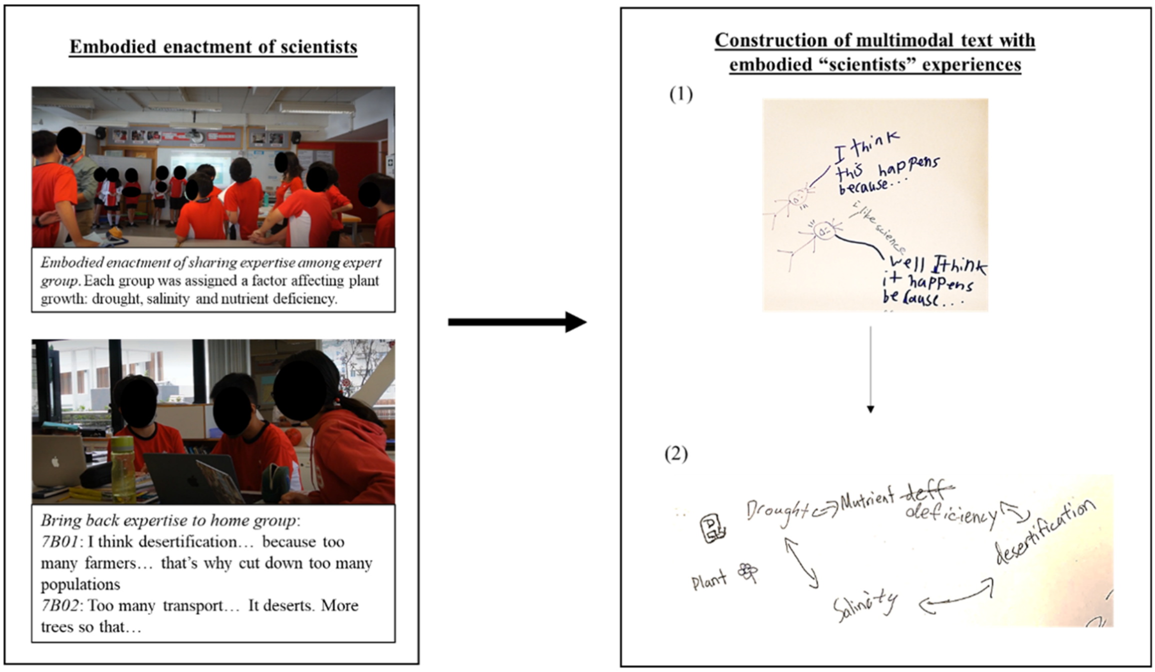
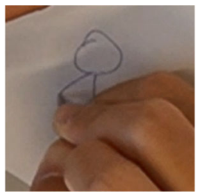
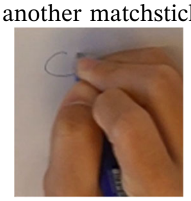
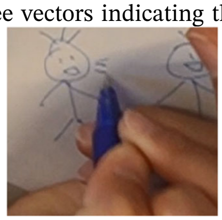
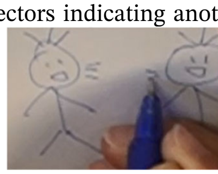


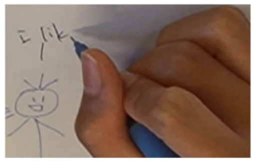
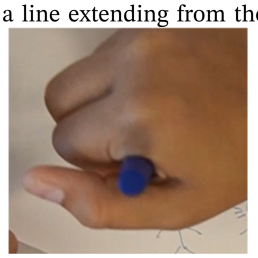
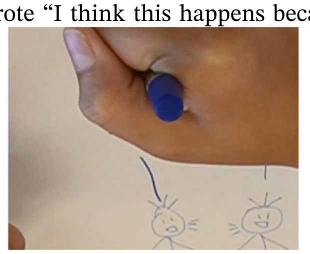
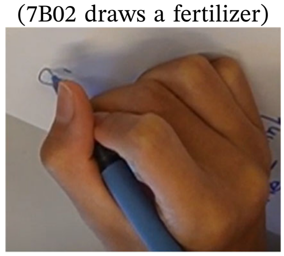
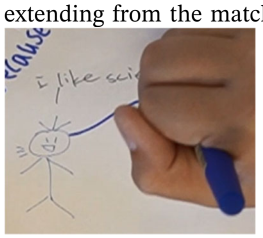
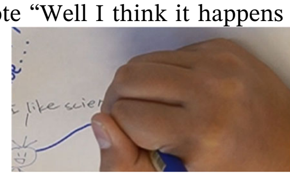

**FIGURE 5** | Embodied semiosis from embodied enactment of scientists sharing their expertise to multimodal construction of texts reflecting on their embodied experiences of social organizations and interactions.

**TABLE 7** | Episode 4: Representing social organizations and interactions (Part 1).

| Turn | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 1 | 45:30 | 7B01: You do drawing (.) People talking science, right? |
| 2 | 45:36 | (7B03 drew a matchstick individual)  |
| 3 | 45:38 | (7B03 drew another matchstick individual)  |
| 4 | 45:40 | 7B01: That is an amazing drawing, right? |
| 5 | 45:41 | 7B03: Of course. |
| 6 | 46:32 | (7B03 drew three vectors indicating the person's talk)  |
| 7 | 46:33 | (7B03 drew three vectors indicating another person's talking)  |

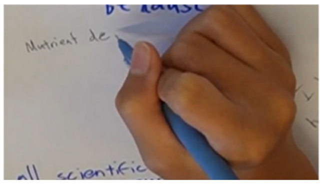
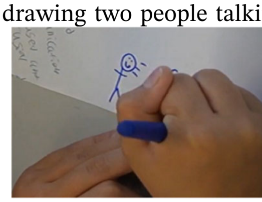
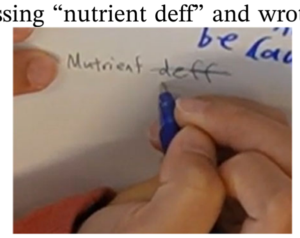
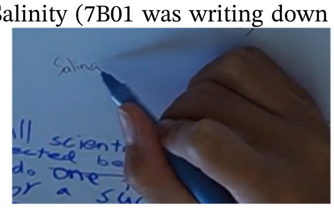
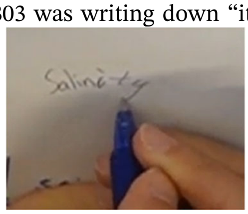
(Continues)

**TABLE 7** | (Continued)

| Turn | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 8 | 46:32 | (7B02 drew a line extending from the matchstick individual.)  |
| 9 | 46:40 | 7B02: I like (.) science (.)<br>(7B02 wrote “I like science”)  |
| 10 | 46:41 | 7B01: Okay. (7B01 drew a line extending from the matchstick individual.)  |
| 11 | 46:43 | (7B01 wrote “I think this happens because …”)  |
| 12 | 46:57 | (7B02 draws a fertilizer)  |
| 13 | 47:01 | (7B01 drew a line extending from the matchstick individual.)  |
| 14 | 47:02 | (7B01 wrote “Well I think it happens because…”)  |

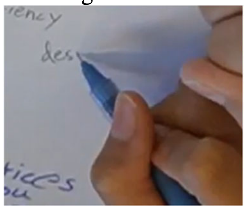
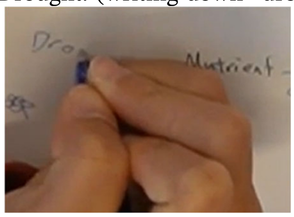
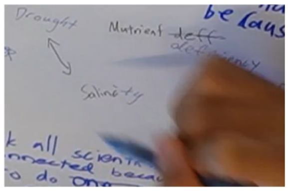
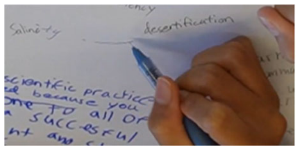
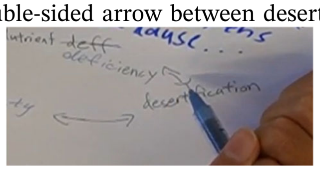
7B03 were then expanded by visualizing the materiality of a flower and a fertilizer (Turns 16). Instances of "doing school" (Jiménez-Aleixandre, Bugallo Rodréguez, and Duschl 2000) were seen as students negotiated the correct spelling of "deficiency" (Turns 16–18) and "salinity" (Turns 23–25), which students considered the task as a procedural display. Afterward, to document the embodied experience of social aspects of science, members chose to use written texts to represent factors affecting crop growth (Turns 16, 23, 25, 26, and 28). The two-sided arrows might possibly show how scientists from three different areas (salinity, drought, and nutrient deficiency) share their research expertise in both ways (Turns 29–31). The

**TABLE 8** | Episode 4: Representing social organizations and interactions (Part 2).

| Turn | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 16 | 47:29 | (7B02 wrote down "nutrient deff")  |
| 17 | 48:09 | 7B02: How to spell "deficiency"? |
| 18 | 48:11 | 7B03: I do not think it spells like that. |
| 19 | 48:15 | (7B01 was drawing two people talking together)  |
| 20 | 48:21 | (7B03 was crossing "nutrient deff" and wrote "deficiency")  |
| 21 | 48:34 | 7B01: I think we can use kool aid. (7B01 was writing down "I think if we use kool aid instead of water ... will happen" on one scientist's speech and "I think this happens because ..." on another scientist's speech)  |
| 22 | 48:43 | 7B02: And? |
| 23 | 48:44 | 7B03: Salinity (7B01 was writing down "Salin")  |
| 24 | 48:47 | 7B02: How to spell? |
| 25 | 48:48 | (7B03 was writing down "ity")  |

(Continues)

**TABLE 8** | (Continued)

| Turn | Time | Verbal utterances (with screen-capturing of writing and drawing processes) |
|---|---|---|
| 26 | 48:55 | (7B02 was writing down "desertification")  |
| 27 | 49:03 | 7B02: There is one more. |
| 28 | 49:04 | 7B03: Drought. (writing down "drought")  |
| 29 | 49:11 | (7B02 was drawing a double-sided arrow between drought and salinity.)  |
| 30 | 49:12 | (7B02 was drawing a double-sided arrow between desertification and salinity.)   |
| 31 | 49:16 | (7B02 was drawing a double-sided arrow between desertification and deficiency.)   |

drawings of the flower and a fertilizer, serve as a semiotic bridge (Pham and Tytler 2021) between the sentence of "I learned how communication can be used is crucial for a successful experiment" and embodied experience of sharing research expertise with other students. Semiotic bridges provide linkages between concrete physical situations and symbolic representations of the interactions (Pham and Tytler 2021; Savinainen et al. 2004). The declarative written statement of the social aspects of science can be linked to the focus group's embodied experiences.

The embodied experiences of students were visualized for the second time in drawings of two matchstick individuals talking (Turn 19), with written mode representing what individuals were talking (Turn 21). The matchstick individuals in fact represented students' embodied experience evidenced by the first-person pronoun "I" in the utterance "I think we can use kool aid." (Turn 21, 7B01) as well as the written sentence "of "I learned how communication can be used is crucial for a successful experiment." Interaction between drawings, texts, and verbal discourse facilitates embodied meaning-making of social aspects of science.

Our interpretation is that engaging students in multimodal explicit-reflective discourse of NOS extended the continuity of embodied semiosis (Violi 2012) of the social organizations and interactions. In the jigsaw activity, students were engaged in interaction and sensations of the bodies, paying attention to moments, interactions, and affective interactions (Taylor 2019) (Figure 5). In terms of embodied sign-making, as a sign, the body allowed students to use gestures, movement, and verbal talk to act like scientists who were exchanging expertise with another group of scientists with different expertise. Specifically, groups of students stand on different sides of the classroom, representing groups of scientists with different expertise researching on their expertise area (e.g., salinity). In the co-construction task of multimodal representations of NOS, students created new signs that were related to the jigsaw activity. These new signs include arrows, written factors affecting crop growth as well as matchstick figures showing how scientists share their expertise. The arrow signified the verbal interaction among groups of scientists with different expertise; the location of different factors affecting crop growth resembles standing position according to their group of expertise; the matchstick figures signified their talk and movement as scientists were exchanging expertise.

Students were motivated to draw matchstick individuals twice to indicate their embodied experiences in learning expertise from the expert group and bringing their newly acquired knowledge back to their home group. The signs in the jigsaw activity were reshaped and linked to the signs in co-construction of social certification and dissemination. Such illustration cannot be realized without engaging students in utilizing visual, verbal, and written modes.

## 6 | Discussion

In this section, we will provide a summary and discussion of the findings. This paper advances research in both NOS and multimodality in science education. It contributes to addressing the research gap around the ways in which students coordinated the visual, verbal, and written modes to make meaning of NOS. Furthermore understanding students' interactions contributes to how the chain of semiosis of NOS works, extending students' meaning-making through signs of NOS in the teaching activity to those in the collaborative multimodal discourse. Followed by the discussion of our findings, we acknowledge the limitations of this study, as well as discussing implications for future research and practice.

## 6.1 | Multimodal Meaning-Making of NOS

### 6.1.1 | The Role of Visual, Verbal and Written Modes in Meaning-Making of NOS

Recent research on students' collaborative multimodal discourse has illuminated the roles of drawing in facilitating meaning-making of NOS (de Andrade et al. 2021; Park, Tang, and Chang 2021; Sjøberg, Furberg, and Knain 2022). The results of this study are also commensurate with the important role of the visual mode in visualizing and concretizing abstract ideas (Sjøberg, Furberg, and Knain 2022). However, this study also revealed that both the visual and written modes enable students' meaning-making of NOS. In fact, similarities were observed across two focal groups of students. For the visual mode, students drew the materiality of artifacts involved in their inquiry activities, such as wheat grass (Class 7A, episode 3) and a flower (Class 7B, episode 4); for written mode, students in both groups layered down a set of methodological rules such as "controlled variables" and "hypothesis" (see artifacts generated in episode 3). Such similarity could be attributed to the reason that these methodological rules were too abstract to be represented in visual mode. Also, for the four NOS categories, the findings also confirm that drawings and written texts juxtapose to facilitate meaning-making of NOS (Cheung and Erduran 2023). This type of juxtaposition also facilitates the verbal discourse of NOS.

Our analysis also adds to the literature about the functions of written mode of representation (see Table 9). With respect to the functions of the written mode, seven new functions were identified, namely correcting, labeling, filling, linking, documenting, recounting, and expanding. Though not a focus of this study, the roles of correcting, labeling, and filling inherit the epistemological framing of "doing schools" or "doing lessons" (Jiménez-Aleixandre, Bugallo Rodréguez, and Duschl 2000; Schellinger, Jaber, and Southerland 2021). It seems that these epistemological framings in the written mode emerge alongside the meaning-making of NOS. In contrast, students used the written mode to link NOS ideas raised by other students, documenting NOS ideas, recounting contextual experience in which students' NOS meaning-making emerges and expanding NOS ideas.

The findings indicate the important role of the written mode of representation. Across all four episodes, simply using the visual

**TABLE 9** | Roles of different modes in meaning-making of NOS.

| Role | Description |
|---|---|
| Verbal mode | |
| Request | To ask other members to draw/write ideas |
| Inform | To state the intention of their drawing/writing |
| Question | To query suggested ideas or representation to others |
| Agree | To accept suggested or represented ideas |
| Reject | To decline suggested or represented ideas |
| Suggest | To propose what and how to write and/or draw |
| Elaborate | To expand conceptual ideas in detail |
| Check | To identify confirmation of suggested ideas/representation |
| Repeat | To tell what they have written or drawn |
| Doubt | To express uncertainty about an idea |
| Visual mode | |
| Visualize | To make the materiality of scientific method, apparatus, and scientists visible |
| Concretize | To illustrate relations between theoretical entities |
| Elaborate | To clarify and sharpen drawing and writing |
| Written mode | |
| Correct | To revise the written texts or drawing according to conventions |
| Label | To set down names to objects and people |
| Fill | To finish incomplete spelling |
| Link | To connect to ideas raised by others |
| Recount | To recall contextual experiences from inquiry |
| Document[a] | To record nature of science ideas |
| Expand[a] | To explain nature of science ideas |

*Note:* Bolded words refer to newly identified functions of modes.
[a]The newly identified functions that facilitates students' representation of nature of science.

mode could not help students make meaning of NOS. In the context of NOS, illustrating cognitive-epistemic and social-institutional of science requires co-deployment of different modes. For example, in representing the diversity of scientific methods (episode 4), students wrote "identify" and "hypothesis." Drawing a cross in between "identify" and "hypothesis" represented that descriptive investigation does not require a hypothesis. Contrasting with previous studies that engaged with students' collaborative drawing (de Andrade et al. 2021; Areljung, Skoog, and Sundberg 2021; Park, Tang, and Chang 2021; Sjøberg, Furberg, and Knain 2022; Tytler et al. 2019), planning for students' group drawing of NOS is not sufficient for them to reflect on their NOS understanding in relation to instructional contexts. Therefore, there is a need for delimiting tasks requiring drawing of NOS and extending these tasks to diverse modes of representation.

#### 6.1.2 | Semiosis of NOS in Collaborative Multimodal Discourse

Importantly, in line with the argument on the role of materiality in meaning-making (Tang 2022), students' co-construction of multimodal representations configures apparatuses and actors in the learning activities of NOS. Other than argumentation (Tang 2022), the findings show that materiality plays an important role in multimodal meaning-making of NOS. Visualizing the materiality of clipboard helped students make meaning of the journal publication process (episode 2); the materiality of apparatuses in scientific investigation helped them contextualize their meaning-making of methodological rules (episode 3); visualizing the materiality of students themselves engaging in science helped them make meaning of the social organizations and interactions (episode 4) (Figure 6). There is a shared agency between mind and materiality in social activities (Latour 1987) through which students negotiated their NOS understanding. In alignment with arguments made by Hetherington et al. (2018) on interaction between minds and materials in science learning, learning NOS also involves such interaction to reinforce a material meaning-making of NOS.

The analysis also evidenced various aspects of semiosis of NOS, semiotic bridges (Pham and Tytler 2021), re-semiotization (Iedema 2001), and embodied semiosis (Taylor 2019). In science education literature, many studies gave attention to language and literacy issues (Wilmes and Siry 2019) and learning disciplinary knowledge (Pham and Tytler 2021). While much of these works address students' meaning-making of disciplinary knowledge, this study illuminates the process of semiosis of cognitive-epistemic and social-institutional aspects of science. For semiotic bridges, as shown in episode 4, the visualization of the materiality of scientific real-life objects acts as a semiotic bridge between embodied experiences and multimodal meaning-making of NOS. The semiotic bridges of NOS are different from learning disciplinary knowledge that disciplinary scientific knowledge that requires translation across different levels of representations (Johnstone 1982). For example, the use of mathematical equations serves as a semiotic bridge between submicroscopic representation and symbolic representation in mole calculation (Pham and Tytler 2021). Another fruitful contribution of this paper is that students can re-semiotize their discursive understanding of scientific practices into multimodal ensembles, as well as making meaning of their embodied experiences and redescribing these experiences with a link to NOS. This could be attributed to the provision of structured opportunities for collaborative multimodal discourse of NOS at the end of instruction. If students are only provided with verbal discourse opportunities, they cannot reflect on their embodied experiences by drawing the materiality of NOS or writing the stages of nature of scientific methods. As such, students have their own multimodal semiotic resources to bridge their learning experiences to explicit reflection of NOS.

### 6.2 | Limitations

This study has three main limitations. First, we only attended to integration of three modes of representation in meaning-making of NOS, namely verbal, visual, and written modes. The analysis in this study provides less information on students' use of gestures in meaning-making of NOS. Gestures can play various roles such as extending the limits and describing entities that are not present in pictures and texts (Sjøberg, Furberg, and Knain 2022). For example, in the absence of a flowchart showing the steps of scientific methods, the steps can be represented by iconic gestures showing the temporal aspect. In this study, we mostly observed deictic gestures in pointing a specific drawing or a text. This can be explained by the fact that we provided a sheet of paper for students to express their NOS understanding using drawings and texts. The study of gestures might not be applicable to this study because the piece of paper mostly facilitates "inscriptions" of drawings and texts of NOS.

Next, as this study adopts a collective case study design, the findings reported cannot be generalized beyond these two groups of students. However, this paper shows the strength of case study which provides a deeper insight into students' use of different modes in meaning-making of NOS. In this way, we identified different themes on how multimodality facilitates semiosis of NOS. Although future research is needed to establish the validity of these findings in other contexts, the themes identified provide an avenue for multimodality research in students' meaning-making of NOS, which is a relatively new area of research.

Moreover, as illustrated in episode 1, students sometimes did not develop an elaborate epistemic understanding of scientific practices. Students layered down a set of scientific practices and expanded the meaning of these scientific practices in the written mode. There could have been more elaboration on how these scientific practices were related in generating, validating, and revising scientific knowledge with reference to the Go Pink activity. However, young multilingual learners (e.g., seventh graders in this study) require much more scaffolds, such as sentence scaffolds in worksheets, in making more elaborate representations of the epistemic basis behind these scientific practices. As the current study did not intend to examine the effectiveness of pedagogical interventions on students' multimodal representations of NOS, future investigations can delve into teaching strategies that improve young learners' linguistic and visual representations of the epistemic basis behind scientific practices.

| NOS categories | Students | Semiotic resources | NOS understanding expressed |
|---|---|---|---|
| Nature of scientific practices (Episode 1) | Class 7A | Drawing<br>Writing linguistic meaning of scientific practices | Expanding meaning of how each scientific practice generates knowledge claim and their interrelations |
| Social certification and dissemination (Episode 2) | Class 7B | Drawing<br>Writing an explanation of journal submission | Bridging their writing scientific reports to scientists' activities such as journal submission |
| Nature of scientific methods and methodological rules (Episode 3) | Class 7A | Drawing<br>Writing names of variables and "hypothesis" | Identifying diversity of scientific methods and relationship between variables and different types of scientific methods |
| Social organizations and interactions (Episode 4) | Class 7B | Drawing<br>Writing the factor for plant growth they were responsible to investigate (home/expert group) | Linking their jigsaw activity to scientists at a research group visiting another research group to learn from other expertise |

**FIGURE 6** | Comparison of findings across NOS categories and focal groups.

## 6.3 | Implications for Practice and Research

With growing focus on the role of different modes of representation of NOS, it is important to examine how these modes interact to contribute meaning-making of NOS. The insights generated in this study will be an avenue for science teachers to design structured opportunities for engaging students in multimodal discourse of NOS. Apart from its contribution to the field of NOS, this study supports that anchoring students' collaborative discussion in drawings is not sufficient for meaning-making of NOS, contrasting with some studies (Park, Tang, and Chang 2021; Sjøberg, Furberg, and Knain 2022; Tytler et al. 2019). There is a need to anchor students in both drawing and writing as they provided for the processes of making meaning of NOS. Future research can explore whether a teaching intervention involving students' iterative composition of multimodal representations of NOS would enhance their understanding of NOS.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### Ethics Statement

This study has received ethical approval by the authors' host institution. All students and their parents consented to participate in this study.

### Conflicts of Interest

The authors declare no conflicts of interest.

### Data Availability Statement

Data is not publicly available owing to ethical restrictions.

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## Supporting Information

Additional supporting information can be found online in the Supporting Information section.