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Undergraduate biology students' model-based reasoning in the laboratory: Exploring the role of drawings, talk, and gestures

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Abstract

This paper reports on a case study of undergraduate biology students' drawing-based modeling and how this process plays out in naturalistic dialogues. Recent research has revealed the importance of drawings, talk, and gestures in students' model-based reasoning. This study provides further insight into the complementary role of these multimodal representations in student' model-based reasoning. The empirical basis constitutes sequences of students' interactive modeling during a laboratory exercise targeted toward the molecular mechanism behind diagnostic tests. The analytical procedure involves a social-semiotic analysis of students' drawings and microanalyses of the sequences of student interaction while engaging with this modeling activity. Our findings reveal a pattern in the use of these representations and provide insights into their roles in students' model-based reasoning. During three critical episodes in the students' modeling process, we show how drawings, deictic gestures, talk, and iconic gestures in a recurring pattern contributed to bringing students' meaning-making forward: drawings contributed to opening a creative space for their reasoning, while explorative talk together with iconic gestures became an important resource in exploring the aspects that were *not* shown in the drawing. We also show how the different representations took on different semiotic loads depending on where in the modeling cycle they were. We show how certain semiotic choices in the first drawing seem to support the students' model-based reasoning. Representing gestures became particularly important when the students revised and extended their models. These findings are discussed in relation to the different affordances of the various modes of representation.

KEYWORDS
drawing, gestures, interaction analysis, model-based reasoning, representations, social-semiotic analysis

1 | INTRODUCTION

This paper reports on a case study on undergraduate biology students' model-based reasoning in a naturalistic laboratory setting and explores the role of different representations (such as drawings, talk, and gesture) in students' meaning-making. The field of science education has witnessed an increased focus on engaging students in scientific practices in recent decades (American Association for the Advancement of Science, 2011; National Research Council, 2012). Modeling can be described as a scientific practice (Osborne, 2014), as a style of reasoning (Kind & Osborne, 2017), and as the defining characteristic of all scientific inquiry (Nersessian, 2008; Windschitl et al., 2008). Modeling thus should be a central part of science education at all levels (Quillin & Thomas, 2015; van Driel et al., 2019).

Compared to other scientific disciplines, such as physics and chemistry, the importance of modeling in biology education is frequently underemphasized (National Research Council, 2012; Quillin & Thomas, 2015), and modeling is often understood in a purely mathematical sense (American Association for the Advancement of Science, 2011). The development of drawings, however, has played a crucial role in biology as a scientific practice (Knorr-Cetina; 1999; Latour, 1999). Drawing also plays an important role in instructional settings in biology education (Quillin & Thomas, 2015; Roth & Pozzer-Ardenghi, 2013), but often without an explicit focus on drawing as a modeling activity (Quillin & Thomas, 2015). Explanations in molecular biology—or models, which are a kind of explanation (Lehrer & Schauble, 2010)—are often two-dimensional representations showing the entities, properties, and activities that constitute them and provide the description of a mechanism (Machamer et al., 2000). Learning to draw such models hence should be an important part of biology education.

Scholars have increasingly focused on the importance of student-generated representations and representational competence in science education in recent years (Ainsworth et al., 2011; Airey & Linder, 2009; Prain & Tytler, 2021; Volkwyn et al., 2020), including biology (Offerdahl et al., 2017; Treagust & Tsui, 2013). According to Prain (2019), the relationship between representations and models and the relationship between students' reasoning and student-generated drawings are important areas that future research on learning with and from representations should focus on. This area is also where the current study will make a contribution. Some recent research has started to reveal the important role of drawings in students' reasoning (Bolger et al. 2012; Knain et al., 2021; Tytler et al., 2020; Wilkerson-Jerde et al., 2014), and more specifically in students' mechanistic reasoning (de Andrade et al., 2021), which is a kind of model-based reasoning. Research has also shown that gestures are important for the development of mechanistic models (Mathayas et al., 2019). The present study contributes insights into the complementary roles of drawing, talk, and gestures in students' model-based reasoning by analyzing students' meaning-making and examining how it develops in students' interactions in a naturalistic laboratory setting.

We combine two analytical approaches in this study to analytically scrutinize students' meaning-making. By taking an interaction analytical approach, we can explore and understand how students' meaning-making is displayed and developed in ongoing interactions between interlocutors (in this particular setting collaborating peers), mediated by talk, gestures, and material tools (Furberg et al., 2013; Jordan & Henderson, 1995; Steier et al., 2019). Taking a social-semiotic approach to students' meaning-making allows us to systematically analyze the nuances of meaning in students' drawings and to tease out *how* the experience of the physical and social setting may be construed as situated semiotic choices in the situation in and across modes (Halliday, 2003; Kress & Van Leeuwen, 1996). The underlying argument for combining these two analytical approaches is an assumption that these foci together can provide an even richer insight into classroom interactions and students' engagement with modeling activities (Knain et al., 2021). The following research question has guided our analysis:

What role do different representations, such as drawings, talk, and gestures, play in biology students' model-based reasoning in a laboratory context?

2 | THEORETICAL BACKGROUND

In the next sections, we first describe our theoretical background, with a focus on model-based reasoning and student-generated representations, before we review relevant studies on the role of different representations for students' model-based reasoning. Finally, we describe the theoretical background for our analytical focus, which is on students' meaning-making while engaging with the drawing-based modeling activity.

2.1 | Model-based reasoning

While several models of modeling instruction exist, what they all have in common is that modeling is a cyclical process of construction, use, evaluation, and revision (Gilbert & Justi, 2016; Lehrer & Schauble, 2006; Schwarz et al., 2009; Windschitl et al., 2008). Much research on models and modeling has focused on students' understanding of models and on conceptual gains from engaging with modeling (Lehrer et al., 2008; Schwarz & White, 2005) or the use of models to communicate content knowledge (Grünkorn et al., 2014; Günther et al., 2019; zu Belzen et al., 2019). Less work has detailed students' modeling practices as they play out in naturalistic dialogues. One naturalistic study focused on student discourse found that the students engaged in distinct modeling cycles ("messing about" and "digging in") that reflected deepening engagement in the modeling task (Wilkerson-Jerde et al., 2014).

Models are deliberately created explanatory representations that often display aspects of a mechanism (Hubber & Tytler, 2013; Schwarz et al., 2009). Model-based reasoning is often described as a creative process that include several practices such as abstractions, generalizations, and improvements involved in the process of model construction and evaluation (Nersessian, 2008). Such reasoning represents a different style of reasoning compared to what we often associate with the "scientific method" (Kind & Osborne, 2017). An important point is that representations are not simply products of reasoning, but are an integrated part of the reasoning process (Lehrer & Schauble, 2010; Windschitl et al., 2008). This idea is also important for our understanding of model-based reasoning in this paper, as we are interested in students' reasoning processes while they develop drawings to understand the underlying explanatory mechanism of diagnostic tests. For instance, through model-based reasoning, we select particular features that are important for a phenomenon's explanation, while we move irrelevant features to the background or remove them (Manz, 2012).

Mechanistic reasoning is a specific form of model-based reasoning that targets the underlying mechanisms of observable phenomena (Krist et al., 2019). Particularly relevant for the present study is Krist et al.'s (2019) identification of three interconnected heuristics (i.e., thinking strategies) that proceed from students' implicit assumptions about mechanisms. In the first heuristic, labeled "Thinking across scalar levels," students typically orient their focus on the underlying factor for a target phenomenon. Indications of this heuristic are typically if the students focus on the scalar level below the observable phenomenon (de Andrade et al., 2021). In the second heuristic, "Identifying and unpacking relevant factors," the students typically orient their focus on what the underlying entities and processes are (2A) and their behaviors and interactions to produce the phenomenon (2B). In the final heuristic, which represents the most complex level of mechanistic reasoning, the students are "linking to coordinate relationships over time and/or place." Indicators of this heuristic may be that students make connections or coordinating relationships between observable phenomena and various underlying factors (de Andrade et al., 2021).

2.2 | Learning from student-generated representations

All models may be considered representations, but representations also include other semiotic resources, such as exploratory talk, gestures, drawings, and the manipulations of artefacts (Hubber & Tytler, 2013). Representations are thus a broader category of discipline-specific semiotic resources that can be used in modeling (Angell et al., 2008; Hubber & Tytler, 2013) and constitute the "language of expression for modeling" (Lehrer & Schauble, 2010, p. 10). Representational competence is thus an important foundation for model-based reasoning. Volkwyn et al. (2020, p. 91) define representational competence as "the ability to appropriately interpret and produce a set of disciplinary-accepted representations of real-world phenomena and link these to formalized scientific concepts." The following review will focus on relevant previous research on the role of different representations (drawings, talk, and gestures) with a particular focus on their role in supporting students' model-based reasoning.

A study by Knain et al. (2021) on secondary school students' drawing processes showed a progression of student-generated drawings from being "naturalistic" toward more scientific versions enabled by the students' orientation towards critical details in the drawing. The findings also showed how both the drawings and students' interactions were crucial for the development of a more sophisticated understanding. Park et al. (2021) investigated how the activity of drawing interacts with verbal discourse during collaborative drawing. They found an alternation between the drawing as a visual mode and the verbal discourse as the students worked through a recurring pattern of planning (verbal), drawing, and evaluating their drawings (verbal). Another study, also focused on student-generated drawings, has shown how certain semiotic choices that students made when developing drawings, such as representing phenomena from a side-view perspective, allowed them to represent depth and thus supported them in developing an explanation of the phenomena (Tang et al., 2014).

Tytler et al. (2020) suggest that student-generated drawings can work as proto-models that require students to engage in model-based reasoning. More specifically, they found that when students developed drawings, they were concerned with the reasoning related to how the model (drawing) corresponded to what was modeled (the observable phenomena) and of the coherence of the model, which are important characteristics of model-based reasoning (Lehrer & Schauble, 2006). This is in line with the findings of de Andrade et al. (2021), who showed that drawings played a crucial role in supporting students' mechanistic reasoning (Krist et al., 2019), for instance by pushing them to look for a mechanism. For example, the authors showed that by asking the students to construct a drawing on particle-level (thereby thinking across scalar levels), the students also began to reason about the entities and their interactions.

A vast amount of research has also documented the key role of gestures as meaning-making resources. Particularly, gestures are well known for being important in linking physical experiences and abstract theoretical language (Roth & Lawless, 2002a, 2002b), which is an essential part of representational competence (Volkwyn et al., 2020). This idea suggests that gestures are important in the process of transduction, which refers to how meaning in one mode is remade in a different mode (Prain & Tytler, 2021). Pozzer-Ardenghi and Roth (2004) pointed to the importance of gestures as meaning-making resources in biology lectures and documented several different functions of gestures in this setting. For instance, they showed how people used some gestures to emphasize certain elements in representations, while they used others to represent elements that were not visually present. Such aspects might include the three-dimensional shape of elements that are only depicted in two dimensions in drawings (Roth & Pozzer-Ardenghi, 2013).

Gestures can also contribute to meaning-making by *adding* aspects not shown in the drawing at all, such as dynamic processes. Representations, such as pictures or drawings, can thus provide background that supports other information that is not observable. Other studies point to the importance of gestures as resources in supporting students' ability to "talk science" (Park et al., 2006; Ünsal et al., 2018). For instance, Park et al. (2006) focused on earth-science group-work activities and showed that students used gestures to illustrate certain phenomena when they were unable to do so with words. Gestures have a temporal and nonpersistent character and have other epistemological commitments than the modes of talk and drawing (for instance) that make them more appropriate to use in certain cases (Fredlund et al., 2021). Mathayas et al. (2019) have shown the importance of representational gestures—gestures constructed to represent phenomena or entities—in the development of mechanistic explanatory models. For instance, they showed how representational gestures can contribute to making underlying mechanisms visible and can support the translation of spatial models to verbal explanations. They argued that representational gestures share some similarities with drawings, in that they can help students think about mechanisms, but they can be used in a more dynamic and embodied fashion (Mathayas et al., 2019).

2.3 | Students' meaning-making: Two analytical approaches

Our analytical focus and unit of analysis in this paper is on students' meaning-making. We believe that this focus on the broader concept of meaning-making can contribute with deeper insight into the role of these representations in students' model-based reasoning. We combine two analytical approaches to explore students' meaning-making.

As an interdisciplinary method, interaction analysis (IA) is rooted in ethnography, sociolinguistics, conversation analysis, ethnomethodology, and sociocultural theories (Jordan & Henderson, 1995). Our interaction analytical approach is based on a sociocultural perspective on learning. A central assumption in sociocultural perspectives is that learning is seen a social and interactional meaning-making process, with an emphasis on the mediating role of semiotic and material tools, or cultural artefacts (Vygotsky, 1978; Wertsch, 1991). Seen from a sociocultural perspective, talk is the most significant tool for making sense of the world and represents what Mercer (2004) refers to as "a social form of thinking." Through social interactions, participants make sense of scientific concepts as well as representations, while also making these interpretations visible to other participants (Furberg & Silseth, 2022; Linell, 2009). Along with speech, gestures are an important semiotic component of meaning-making. Not only as a pervasive mode of interaction, but also as a deeply integrated component of human cognition (Roth & Lawless, 2002a, 2002b).

In the present article, we are concerned with gestures in the sense of idiosyncratic and spontaneous movements of the hands and arms that accompany speech. To provide a deeper understanding of the intertwined character of talk and gestures in students' meaning-making, we focus on chosen gesture functions from the framework proposed by Pozzer-Ardenghi and Roth (2004). These gesture functions will be further discussed in the section outlining our analytical frameworks and procedures.

Halliday (2003) also sees language as a meaning-making resource, where meaning is realized through linguistic choices that draw on language resources in a social context and construe both a physical and social world. Lemke (1990) and Kress and Van Leeuwen (1996) have extended Halliday's linguistic theory to involve not only language but also all sign-making in a multimodal social-semiotic theory. Each mode of representation has different affordances for meaning-making (Kress, 2010; Kress et al., 2001) with some modes appropriate for communicating temporal aspects, properties, and processes, whereas others are more appropriate for communicating spatial relationship and relative size.

From a multimodal social-semiotic perspective, an important point is that scientific concepts *must* be represented through several modes in order for them to be adequately conceptualized (Tang et al., 2011) as different modes of representation contribute different information and meaning (Tang et al., 2011). In Kress et al.'s (2001) work, students' use of signs is *motivated*. Choosing a particular representation is not only a matter of selecting the correct scientific expression but also of negotiating tensions between semiotic resources, for instance between students' own interpretations, the teacher's sign-making, and other students' interpretations (Kress et al., 2001).

3 | RESEARCH DESIGN

3.1 | Empirical context

The empirical context of this case study is a developmental project involving an instructor–researcher collaboration between a biology course instructor (professor) and a science education researcher (the first author of this paper). The instructor is a well-established professor in biology and the current lesson was a part of the bachelor program in biology at a Norwegian university. In the current study we focus on student-generated drawings as part of the students' investigation of the design and function of diagnostic tests, such as pregnancy and ovulation tests. The students were to explore and model the molecular design of these tests in an iterative sequence in small groups. Before the laboratory exercise presented in this study, the researcher and leading instructor met to discuss the details of the lesson. Based on recommendations from the literature on how to support students' representation construction (Tytler et al., 2013), the instructor's scaffolding focused on supporting the students' drawing activity by explicitly discussing representations with the students, supporting them in making connections between the representations (practical exercise, theoretical diagrams of enzyme-linked immunosorbent assay [ELISA], and their own drawings), and arranging plenary drawing sessions where student-generated drawings were presented and discussed.

3.2 | The molecular biology of diagnostic tests

The aim of the laboratory lesson was to illustrate the unique characteristics of antibodies as well as their usefulness in the development of biotherapeutics and diagnostics. Antibodies are often found with an enyzme-linked immunosorbent assay (ELISA) in diagnostics. For instance, ELISAs are used to diagnose disease through the detection of virus-specific antibodies against HIV in blood samples and, more recently, SARS-CoV-2. Pregnancy tests, in contrast, contain antibodies that detect the human chorionic gonadotropin (hCG) antigen (see Figure 1). The tests are designed in a similar way, with a test line and a control line, and are both based on the molecular interactions between antibodies and antigens. The tests also depend on the type of antibodies and how specific they are when antigens are binding. The specificity of the tests relies on monoclonal antibodies that only bind to hCG and no other similar hormones. During pregnancy, urine samples contain hCG, which will bind to labeled antibodies in the application area of the tests. The antibodies then travel along the membrane in the pregnancy test by capillary forces and bind to immobilized monoclonal antibodies in the test line. The molecular binding in the test line is therefore a “sandwich,” with hCG (antigen) in the middle. Further, some labeled antibodies will continue to travel along the membrane and bind to immobilized polyclonal antibodies in the control line. Because these antibodies are polyclonal, they can bind directly to the labeled antibody, thus creating a line that only indicates that

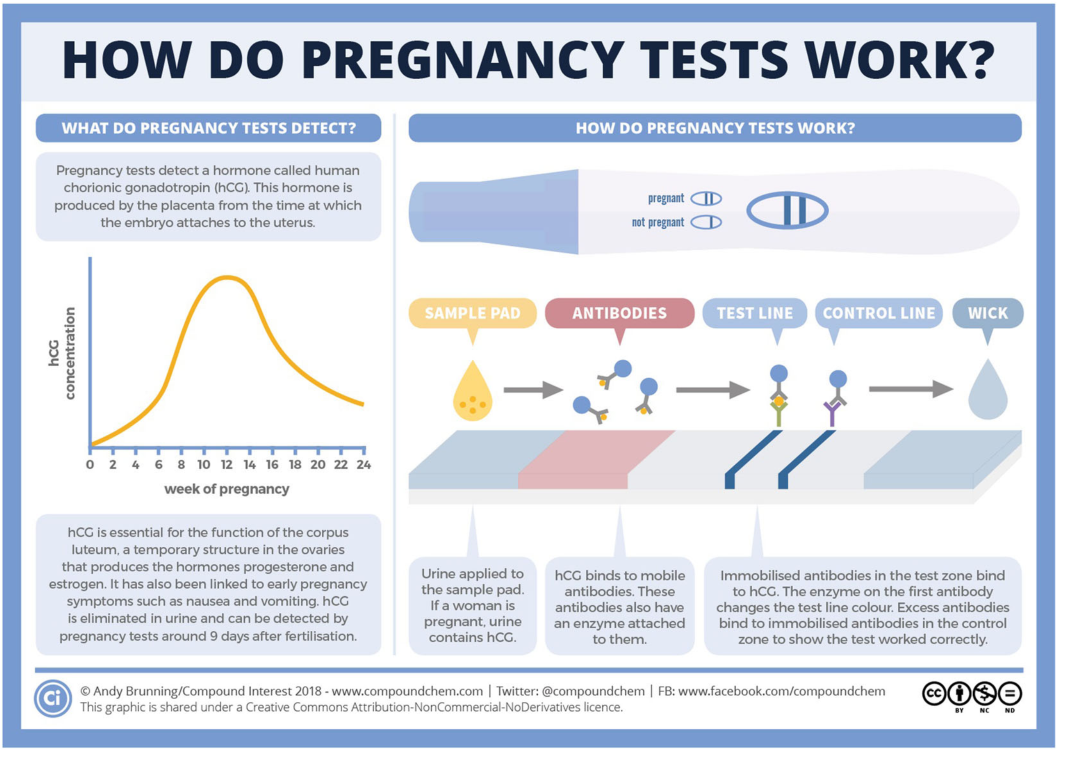


FIGURE 1 Explanation of the molecular mechanisms behind pregnancy tests (Compound Interest, 2018)

the test has been conducted correctly. The molecular mechanisms behind the test and control line are therefore different.

3.3 | Description of the teaching unit

The lesson started with a 45-min introductory lecture followed by 5 h in the laboratory. Students were provided with different pregnancy tests from various pharmaceutical companies (see Figure 2a). During the laboratory session, the students experimentally explored the sensitivity of the pregnancy test and developed drawing-based models to explore their molecular mechanisms (see Table 1 for an overview of the lesson).

The lead instructor asked the students to read each test's instruction manual to decide which concentrations of the hCG hormone they wanted to test to investigate the sensitivity of the test. During a plenary discussion, the instructors and students agreed on a group plan (see Figure 2b) that showed which concentrations they would test and provided an overview of all the different brands of tests (three different brands). All students performed two or three tests as part of the group plan. After the testing sequence, all pregnancy tests were placed on a table and arranged according to treatment and brand (see Figure 2a). The leading instructor led a discussion about the analyses of the results.

The students were then asked to start drawing, with a focus on how the test line appeared. After the students had worked on this for a while, the lead instructor asked if some of them would like to draw the design of the test line on the blackboard (during the plenary drawing session). One group of students volunteered. This session was followed by a discussion about the drawing led by the instructors. The students were then guided to explore and draw the design of the control line as well as the appearance of the color in such tests. Another plenary drawing

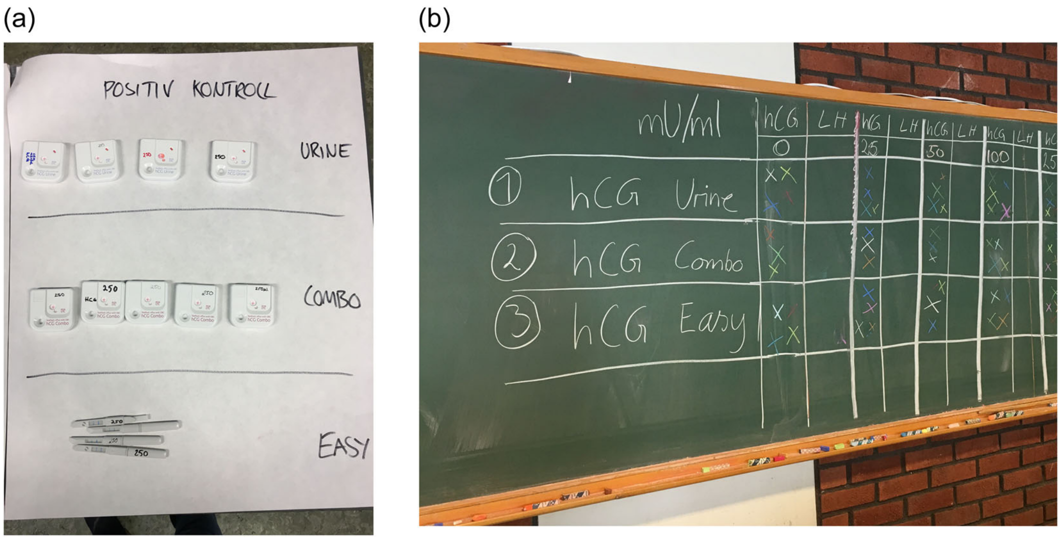


FIGURE 2 Some of the pregnancy test results (positive control) and the group plan on the blackboard. Note the different designs of the pregnancy tests

TABLE 1 Overview of the parts of the lesson. The selected episodes are all from the drawing session.

Part of the lesson	Content
Introductory lecture	Structure of antibodies
	Antibodies in biotherapeutics
	Enzyme-linked immunosorbent assay (ELISA)
Laboratory experiment (sensitivity of pregnancy tests)	Design of the experiment and creation of a group plan
	Implementation of experiment: each group performs tests
	Plenary discussion of results
Drawing session	Introduction to the drawing task
	A group of students makes a drawing of the pregnancy test on the blackboard, with a focus on the test line
	Instructor leads a discussion about the drawing
	Another group of students makes and presents a drawing of the control line

session was arranged in which a different group of students explained the appearance of color in the test using the previous drawing on the blackboard. The students presented their own drawings, followed by further discussion with the instructors. Table 1 shows an overview of the lesson.

3.4 | Methods and data

The main data material for the study consists of transcribed video recordings of two student groups' interactions during the 5-h laboratory task. Most of the groups were made up of three students; a total of 23 student groups participated. The students chose their own groups. Two student groups were randomly selected to be video-recorded; one group included three male students and the second consisted of three female students. A head-camera was placed on one of the students in each group in addition to a camera mounted on the wall beside each group to capture the whole group setting. One camera also captured the lead instructor (who wore a microphone) as well as all the plenary activities and provided an overall view of the laboratory activities. The researcher (the first author) was present and took ethnographic-like field notes, captured pictures of the students' drawings during the process, and collected the students' final drawings; this researcher only had an observatory role.

The analysis of the video data was conducted in two phases. During the initial phase, the video recordings of both groups were examined. In the second phase, in accordance with the present study's research question, we selected one of the two groups for further study, including detailed microanalyses. We selected one group over the other for two main reasons: they effectively created several self-produced representations and were verbally active during the modeling process. We consider the fact that this group consisted of males as irrelevant and will not try to make inferences based on gender.

In this case study, we performed detailed analyses of the interactions that occurred between the three students—Hans, Bob, and Karl (pseudonyms)—during the modeling activity. They were all in their early twenties, and we met them in the last year of the bachelor program in molecular biology. We use the notion of *interaction trajectory* to describe the analysis of interactions over time (Furberg et al., 2013). By analyzing excerpts from the students' interaction trajectories, we can illustrate how the students' modeling developed, and we can describe the role that drawings, talk, and gestures played in their modeling. We have selected excerpts that describe critical points in their modeling process. In accordance with our focus on the role of representations, we have also selected excerpts from settings where the students engaged with these representations and where their interactions were particularly transparent. Because we also captured pictures of students' drawings during the process, we paired the drawings to the selected excerpts for the analysis of the student-generated drawings. We selected three interaction excerpts from the trajectories that were all a part of the drawing session (see Table 1).

3.5 | Analytical framework and procedures

Because the aim of this study is to understand the role of different representations as semiotic resources in students' model-based reasoning, we have applied a combination of two analytical approaches: social-semiotic analysis (Knain et al., 2021; Tang, 2020; Tang et al., 2019) was applied to analyze the visual realization of students' drawings, while IA was applied to understand the role of different resources in students' interactions (Furberg et al., 2013; Jordan & Henderson, 1995). The combination of these two analytical approaches is particularly fruitful when studying how students collaboratively construct, evaluate, and revise representations and can provide deeper insights into students' engagement with representations (Knain et al., 2021).

IA is a sequential analysis where each utterance is considered in relation to an interaction as it unfolds; the primary focus is not on the meaning of each individual utterance but on how meaning develops in the exchange of utterances, together with the deployment of other representations in students' interactions (Mercer, 2004). Because the focus is primarily on how utterances are interpreted by other participants, this focus contributes to the validity of the analysis (Peräkylä, 1997). IA depends on video technology, which provides an opportunity to replay sequences over and over and thus contributes to avoiding confirmation bias during analysis. We relied on a few gesture types from Pozzer-Ardenghi and Roth's (2004) proposed framework to provide insights into the role of the gestures the students used in their interactions (see Table 2). These gesture types can be described as either *deictic*, which are used in concrete or abstract pointing, or *iconic*, which bear perceptual similarities to concrete entities, processes, or events.

Social-semiotic theory examines meaning in all its appearances (Kress, 2010; Kress et al., 2001) and can thus provide a language for describing communication through various representational modes, as well as nuances in

TABLE 2 Gesture functions (adapted from Pozzer-Ardenghi & Roth, 2004)

Gesture type	Description	Type
Pointing gestures	Pinpoint specific aspects of a drawing	Deictic
Highlighting gestures	Draw attention to an area or object; often have a more generic shape, usually circular or elliptical; often used to focus someone's attention	Deictic
Extending gestures	Used to explain entities that are outside the visible limits of the picture	Deictic
Emphasizing gestures	Draw attention to a representation's specific entities by mimicking the shape of objects and, consequently, bringing certain aspects to the foreground and moving others to the background	Deictic and/or iconic
Adding gestures	Used to describe entities not visually present but that could have been there	Iconic
Representing gestures	Represent objects and phenomena that are not directly available in the drawing yet are associated with some feature of it (e.g., the three-dimensional aspect of objects)	Iconic

TABLE 3 Categories of semantic relationships in student-generated diagrams (modified from Tang, 2020)

Main category	Relationship
Movement	• Arrow, path line, wavy lines • No movement
Association	• Independent: no visible connection • Conjoining: physical connection by joining line or adjoining relationship • Analytic: part–whole relationship
Spatial	• Position • Alignment • Relative size and scale • Framing: what is included and what is left out
Perspective	• Dimension: 1D, 2D, or 3D • Angle: portraying visual objects as seen from a particular angle (top-view, side-view, oblique) • Abstraction: portraying visual objects visible with the naked eye (macroview) or not visible with the naked eye (microview) or based on social conventions (symbolic view); any realization of the micro, macro, or symbolic view through layering
Modality	• Formality: depicting credibility of visual objects by drawing them cartoonishly (low modality) or schematically (high modality) • Simplicity: depicting credibility of visual objects by the use of shades and color to provide realism (low modality) or schematic sharp lines (high modality) • Foregrounding: some element is highlighted or made salient through composition, color, size, layering, or conjoined relations
Connective	• Temporal (indicating passage of time) by numbering, arrows, or ordered juxtaposition (left to right or top to bottom) • Comparative

students' representational choices (Tang, 2020). We relied on a social-semiotic analysis of students' drawings to analyze their drawings. Based on principles for visual analysis presented by Kress and Van Leeuwen (1996), different scholars in science education have developed analytical tools to understand the ideas communicated through student-generated drawings (Knain et al., 2021; Tang, 2020; Tang et al., 2019). For instance, Knain et al. (2021) showed how certain analytical concepts, such as *mode*, *framing*, *foregrounding*, and *coding-orientation*, were fruitful for investigating the progression of student-generated drawings. Tang et al. (2019) used an empirical data corpus of student-generated drawings to develop an analytical framework for the ideas communicated through students' drawings. In our analysis of students' drawings presented in this study, we have primarily relied on the above framework (see Table 3; for further details, see Tang, 2020). We have also used the analytical concepts of *framing* and *foregrounding* (Knain et al., 2021) in our analysis to increase the specificity of Tang's (2020) categories. Table 3 presents the framework, which consists of six categories of semantic relationships typically communicated through visual diagrams.

4 | RESULTS

As mentioned above, we focused closely on one group of students: Hans, Bob, and Karl. Before the first episode, the lead instructor had asked them to begin by exploring the test line once they were finished with the practical experiment. Bob made a drawing in his own notebook that was later transferred to a new paper. Materials from the practical exercise, pregnancy test instruction manuals, laboratory instructions, and a large piece of paper (for writing and drawing) were placed on the bench in front of them while they worked.

4.1 | Episode 1: The students' first draft

Before the first episode began, Bob had completed the following drawing (see Figure 3). We will provide a short analysis of the ideas communicated via visual realization in the drawing to explore its role in relation to other representations.

The drawing shows a pregnancy test and what happens inside it at the molecular level (combined macro/micro *perspective* through layering). The pregnancy test was drawn schematically (*high modality*), seen from a top-view (*angle*), and can be recognized as the pregnancy test in the macro world through the rectangular shape. Through the convention of reading from left to right in Western culture, this reading path creates a sequence of Stages (1–3) that represents snapshots of a temporal sequence (*connective*: *temporal sequence from left to right*):

1. The first stage shows two antibodies (*symbolically* drawn as “Y”) and two small red dots (representing hCG molecules) located at different parts of the pregnancy test (*independent relationship*); the red color makes the dots salient.

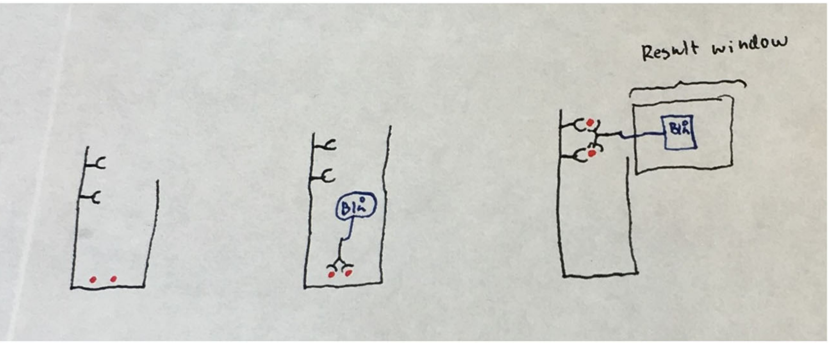


FIGURE 3 The students’ first draft made by Bob

2. The second stage depicts another antibody (Y), labeled with the color blue (*blå* in Norwegian), binding to the hCG molecules to form a complex (*conjoined relationship*).
3. The third stage illustrates that this complex (hCG molecules/antibody, labeled with color) has moved and bonded to the other antibodies (new *conjoined relationship*).

In (1) and (2), the development is in the micro world, and the macro is static. In (3), however, the micro and macro are connected as a third layer, the conjoined "result window."

The following interaction occurred while the students discussed Bob's drawing. They agreed that the drawing represented what the instructor had asked them to do, namely to draw how the test line appears, as indicated by the blue color in the result window in the drawing. See Table A1 in the Appendix for a description of the transcript notations.

Excerpt 1

(1)	*Hans*	So if you have ((*points to the complex in the second part of the drawing and keeps his finger there until line 3*)), I'm not sure if it works this way, but (.) if it's possible to get (.) eh (.), they don't change conformation when they bind?
(2)	*Bob*	Hmm.
(3)	*Karl*	But (.) they become mobilised when they bind, as it's written. ((*Refers to what is written in the instruction manuals.*)) [So are they in...]
(4)	*Hans*	[So maybe they just follow] the concentration gradient? ((*Makes a moving gesture with his whole hand.*))
(5)	*Karl*	Yes, that's possible—that it's osmolarity, or something like that?
(6)	*Hans*	And since it has high specificity ((*points to the antibodies in the result area*)), no (.), high affinity here (.); they bind ((*moves his pen back and forth between the two antibodies that have bound together*)), and then they gather there ((*lifts his finger from the drawing and makes a gesture connecting his thumb and pointer finger*)).
(7)	*Bob*	Hmm ((*in a confirmatory tone*)).
(8)	*Hans*	And then you see the line ((*makes a gesture to indicate a line*)).
(9)	*Karl*	Hmm ((*in a confirmatory tone*)).

In line 1, Hans points to the complex in the second part of the drawing and states that he is unsure about this, but then he suggests that they "change conformation when they bind." Karl continues to explore what happens at this particular point by adding "they become mobilised when they bind" (line 3), referencing what the instruction manuals show. At this point, Hans is still holding his finger on the molecules drawn in stage two, but he then lifts his finger, turns towards Karl, and says, "So maybe they just follow the concentration gradient?" while making a moving gesture with his hand performed with a stable pace. This gesture thus adds a dynamic process to the nominalization "concentration gradient" as well as the static drawing and hence shows that what they are concerned with is explaining *how* the molecules move from the second to the third part in the drawing. Karl adds, "Yes, that's possible. That it's osmolarity".

Hans almost interrupts Karl (line 7) when he quickly leans over to the drawing again and points to the molecules (in the third part of the drawing), thereby showing that he now wants to move the focus over to this part. He says, "And since it has high specificity, no, high affinity here, they bind" and moves his finger back and forth between the molecules to *emphasize* specifically where this binding occurs (between antibody/hCG molecule). He adds, "They gather," now lifting his finger from the drawing and making an *adding* gesture by connecting his thumb and pointing finger to illustrate the process of gathering. Finally, he says, "And then you see the line," while making a gesture *representing* a line. Hans performs his gestures in lines 6–8 in sequence as he explains how the single molecular interaction displayed in the third part of the drawing is connected to the observation of a line in the pregnancy test; he thus links a coordinate relationship between micro and macro.

In the first part (lines 1–5), they are concerned with explaining *how* the molecule moves from the second to the third part of the drawing, which is not shown in the drawing. They use talk to share ideas about mechanisms in this "explanatory gap" by naming mechanisms of movement such as "osmolarity" and that the antibodies "follow the concentration gradient"; they use *adding* (iconic) gestures to illustrate further aspects of this dynamic process (direction and steady pace). The focus of this part of the interaction is thus on exploring the properties, behaviors, and interactions of the underlying entities, which is the second heuristic of mechanistic reasoning (Krist et al., 2019).

In the next part of the interaction (lines 6–8), they return to the drawing and open a new space for reasoning. Hans points to the molecular interaction in the third part of the drawing and adds a property (high affinity) to the molecules that can explain the molecular binding. He *emphasises* the connection between molecular binding and the blue color in the result window while saying "They bind." He then uses *adding* gestures to illustrate that the molecules are gathering while saying, "They gather." This scenario serves to illustrate that even though their drawing only shows a single molecular interaction, several molecules are necessary to observe a blue line in the pregnancy test. Finally, he also uses a gesture representing the observations of "a line" to bring aspects of the observations to the foreground. This part of the interaction hence also focuses on extending the meaning of the drawing by transcending the layering (micro and macro) and building a synthesis so that the molecular binding (the "sandwich") can be perceived *also* as a blue line. This part of the interaction plays an important role in linking the underlying molecular interactions with the observable aspects of the phenomena, which is the third heuristic in mechanistic reasoning (Krist et al., 2019).

Our analysis of the drawing showed that the students were able to establish a visual story of how molecular binding at the microlevel related to the blue color in the result window. The analysis of the students' talk and gestures also showed that what they were mainly concerned with were those aspects that were *not* shown in the drawing: first, how the molecules interact and move, then on the connection between the molecular interaction and the observation of a blue line. The analysis thus reveals a pattern in the use of these representations. The drawing, tentatively representing their current understanding, also seems to open a creative space for collective meaning-making; the students used deictic gestures to keep the focus on specific details, while they used explorative talk and iconic gestures to collectively explore further aspects related to the molecular mechanisms.

4.2 | Episode 2: Students' evaluating models

Once the students had made their first draft, the lead instructor asked if someone would attempt to draw the test principle on the blackboard. One group of students went to the blackboard and made a drawing of the principle (see Figure 4). After finishing the drawing, Hans, Bob, and Karl went to the blackboard to examine it; in the present episode, they stood in front of the blackboard, discussing this drawing. Before we present the excerpt, we will provide a short description of the drawing on the blackboard.

This drawing also shows a temporal sequence (*connective*) with different snapshots of a pregnancy test (top to bottom), and it includes arrows to illustrate this temporal sequence. The students used combined macro/micro layering (*perspective*) to connect what happens inside the pregnancy test at the molecular level (micro level) with the observations (macro level). The drawing shows that antigens (small pink dots, not easily visible in this picture) are located between the antibodies in the test area. This conjoined *relationship* between antibodies and antigens (to indicate molecular binding) is the same relationship as the one depicted in the drawing from the first episode (the 'sandwich'). The drawings therefore communicate many of the same ideas but in a slightly different manner. This drawing, however, also includes a control area (written *kontroll* in Norwegian), which was not included in their own drawing. This episode therefore also represents a turning-point in the modeling process.

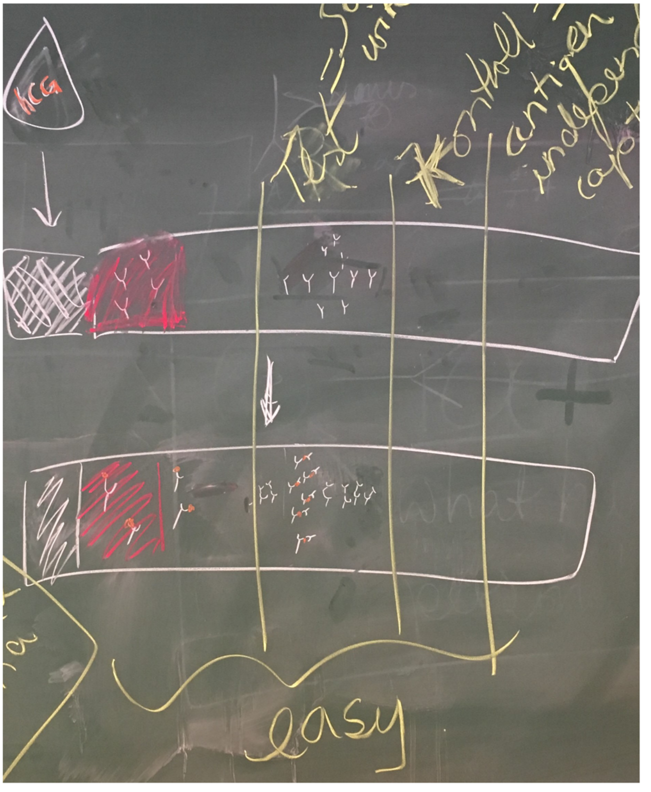


FIGURE 4 Drawing on the blackboard from the first plenary drawing session

Excerpt 2

(1)	*Hans*	Not sure if I understand what this is. ((*Points to the antibodies/antigens in the test line in the lower pregnancy test.*)) Ah yes, those are the mobilised ones ((*points to the same antibodies*)), and those are the ones that have bound to the antigen. ((*Points to two antibodies that are located more to the left.*))
(2)	*Bob*	So, when they bind to the antigen ((*points to the antibodies to the left in the upper pregnancy test*)), they become mobilised and… ((*Moves his finger from the antibodies in the upper part of the drawing down to the two antibodies in the lower pregnancy test.*))
(3)	*Hans*	And they must only be mobile ((*points to the antibodies to the left*)) when they've bound ((*moves his finger to the antibodies in the test area*)); otherwise they'll become mobilised and will bind…
(4)	*Karl*	In any case.
(5)	*Hans*	In any case.
(6)	*Bob*	Are we supposed to make one drawing for each test? Is that what they're asking?
(7)	*Hans*	I think so.
(8)	*Bob*	Then we have to (.). I just made a general one.
(9)	*Karl*	Yeah, right.
(10)	*Hans*	Yeah, but it works fine (.) if it's (.) yeah, it is right.
(11)	*Hans*	But this one had two lines ((*points to the lower test and makes a gesture showing two lines on top of the test*)), and ((*moves his finger to the upper test*)) if there was only one line (.), it was not positive. So that must be something.

(12)	*Karl*	Yeah, it must be something like when they get liquid on it (.), a reaction happens (.), which makes…
(13)	*Bob*	Well ((*points to the upper test*)), 'control' is written here.
(14)	*Karl*	We could have tested it by pouring water on it or something.
(15)	*Hans*	Yes ((*continues to look at the drawing*)), here's a sandwich. ((*Makes an emphasising gesture over the test line in both tests.*))
(16)	*Karl*	Yeah.
(17)	*Hans*	It was written in the book or in the manual ((*holds his finger over the control line*)) that if it was only on this one (.), it was not positive. ((*They all stand and look at the drawing for some time.*))
(18)	*Bob*	Yeah, shall we go back and draw?

Hans starts this interaction by pointing to specific underlying factors in the drawing and naming them: "Those are the mobilised ones," and "those are the ones that have bound to the antigen." Bob continues, focusing more on describing how they behave and interact: "So, when they bind to the antigen, they become mobilised," while using a gesture that shows the molecules' *path* through the pregnancy test, thus *adding* a dynamic process. But Hans interrupts Bob by saying, "And they must only be mobile when they've bound; otherwise they'll become mobilised and bind…" Bob then finishes Hans's sentence: "In any case." Talk is thus used to suggest a conditional aspect of the mechanism.

For a short while, they start to discuss aspects of the task (lines 6–10) and if they will draw a specific test or a general test. Hans turns their attention towards the drawing again by saying, "But this one had two lines," (line 11) while making a gesture that *emphasises* the two parts of the drawing marked as "test" and "control." They seem not to have understood that all the tests actually have two lines, which may have been because in their own test, the two lines made a plus sign instead of two separate lines. Hans adds, "If it only got one line, it was not positive, so that must be something." Karl does not yet seem to be affected by Hans's observation but continues to explore the idea that the important mechanisms lie in the binding and movement: "Yeah, it must be something like when they get liquid on it, a reaction happens." Hans continues with his observations of the drawing, noticing aspects they have not included in their own drawing, and says, "'Control' is written here" (while pointing to this area). This part of the interaction, where Hans and Karl are talking through each other, shows an important turning point in their modeling process: on the one hand, they have presented a hypothesis that the antibodies only become mobilised when they have bound to an antigen; on the other hand, they are starting to see that the phenomenon includes other aspects at the macro level (control line) than what they included in their first drawing. Karl suggests an empirical investigation to test his hypothesis by pouring liquid on the test (and observing if a line appears). But Hans responds to Karl's suggestion by referring to the instruction manual, which states that the test is *not* positive if there is only one line, while pointing to the control area in the drawing. Finally, Bob suggests that they should go back and draw.

This student interaction reveals the same pattern in the use of representations; *pointing* gestures keep the focus on specific details in the drawing while talk is used to explore these aspects. The students also use talk and iconic gestures to explore aspects that are *not* shown in the drawing. Even though the pattern repeats, talk plays a larger role in this episode, where they realize that the target phenomenon includes more aspects that they have not yet accounted for. This episode is therefore an important for the revision (extension) of their model which takes place in the next episode.

4.3 | Episode 3: Revising the model

This episode occurred after the plenary discussion of the test line in the drawing on the blackboard. In the following excerpt, the students explore how the control line appears. In the interaction, they use a drawing Hans has made in his own notebook; below we provide a short description of this drawing, since it is an important reference point in the interaction (see Figure 5).

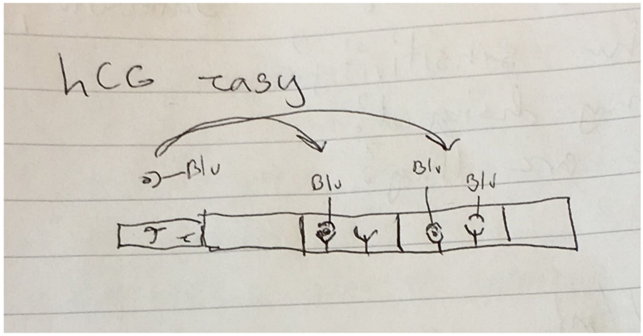
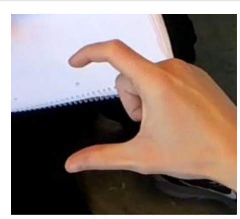
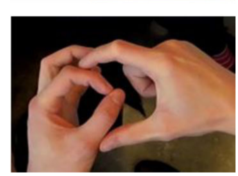


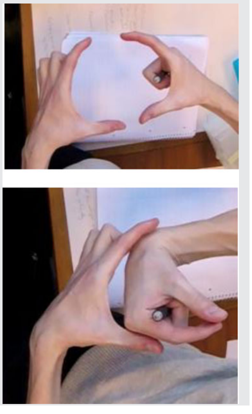
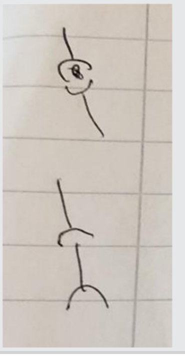
FIGURE 5 Hans's notebook drawing

This drawing shows a particular type of a pregnancy test labeled "hcg easy" (for a picture, see Figure 2a). The pregnancy test has an application area to the left and a test- and control area to the right. As in the other drawings, a combined micro/macro layering is used. The macro layer has evolved towards a closer resemblance to the user interface of the test, compared to the first drawing, where the control line (only) was an add-on (third, right drawing). The micro layer contains a new shift in how molecular processes are represented. In the first drawing, the order from left to right represented processes going (and further in gestures). The blackboard drawing introduced arrows to indicate processes from the top down (connective). In the above representation, arrows indicate the movement of molecules from the application area and towards the test and control areas.

In the following interaction, the students start by examining their own initial draft (Figure 3) while they use extending gestures to indicate the need to include a control line in their drawing. The discussion starts by focusing on how the molecules bind in this line.

Excerpt 3

(1)	*Hans*	But how do they bind to… ((*Points to the third stage in Bob's drawing and looks up at Karl.*))	
(2)	*Karl*	They bind to the antibody instead of the antigen (.), so they bind anyway.	
(3)	*Hans*	Yes ((*looks down to his own drawing*)), but how does it make a difference? ((*Points back and forth between the test and control line in his own drawing.*)) This is used as ((*points to the control area, then to the test area and back to the control area again*)) a control window.	
(4)	*Karl*	Yes, because in the control ((*points to the control in Hans's drawing*)), it will have (.) those antibodies anyway. ((*Makes the first representing gesture shown on the right.*)) It doesn't have to be bound to the antigens. ((*Makes the other representing gesture.*)) So that one ((*points to the control area*)) will appear anyway. But this one ((*points to the test area*)) will need to have the antigen bound.	 

(5)	*Hans*	Yes, but how does it work? ((*Points back and forth between the control and test line.*))	
(6)	*Karl*	It must be that this one ((*points to the control line*)) binds to the antibody, and this one ((*points to the test line*)) binds to the antigens.	
(7)	*Hans*	Yes, so here ((*points to the control line*)), it's antibodies binding antibodies?	
(8)	*Karl*	It must be like that.	
(9)	*Hans*	And here, it's a sandwich. ((*Points to the test area.*))	
(10)	*Karl*	I think so (.). That's the only thing I'm able to see.	
(11)	*Hans*	So that's the mechanism in the first part of the window. ((*Leans over to Bob's initial drawing and points to the result area.*))	
(12)	*Bob*	And then in the other window, it's more like…	
(13)	*Hans*	Then would it be more like this ((*makes the upper gesture shown on the right*)) rather than like this? ((*Makes the lower gesture.*))	
(14)	*Karl*	That it binds to only the other.	
(15)	*Hans*	That it binds ((*starts to draw and speaks while he draws*)) even if (.) okay (.), so this is the first one ((*refer to the drawing to the upper right*)). Then, you have this one in the middle (.), while in the other one, it's more (.) eh (.) maybe that it just binds ((*points to the drawing to the lower right*)) like that or something?	

In the first line, Hans points to Bob's drawing while asking, "But how do they bind to…" and looks up at Karl. Karl seems to interpret Hans's question to be how the molecules bind in the control area (which is not shown in Karl's initial drawing) and answers that "They bind to the antibody instead of the antigen, so they bind anyway." Hans then shows his own drawing (Figure 5), which shows the whole pregnancy test, including the control area, and asks, "But how does it make a difference?" while pointing back and forth between the test and control lines. Then he adds, "This is used as a control window," while he points to this area. Karl responds to Hans's request of exploring what happens in the control area and starts to come up with ideas about the molecular binding. First, while pointing at the control area in the drawing, he says, "Yes, because in the control," then shifts his hands using a representing gesture showing an antibody while saying, "it will have those antibodies anyway." He continues, now including his other hand to represent an antigen while saying, "It doesn't have to be bound to the antigens." He thus uses representing gestures to describe the three-dimensional structure of the molecular interaction that they had already described in two dimensions in their first initial drawing, and thereby invents a “gesture language” to describe the molecular interactions.

Then he continues, pointing to the drawing again, “So that one will appear anyway,” while pointing to the control, “but this one will need to have the antigen bound,” pointing to the other test area. Hans indicates that he still is not satisfied with Karl's answer by asking, “Yes, but how does it work?” Karl has not actually described the molecular interactions in the control line yet, only that the antibodies does not need to have an antigen bound to it. Karl continues to explore while pointing to the control in Hans's drawing: “It must be that this one binds to the antibody,” then moves his finger to the test line, stating, “and this one binds to the antigens.” This explanation seems to have triggered Hans's understanding, and he now tries to reformulate these ideas by being more explicit about the molecular interactions: “Yes, so here it's antibodies binding antibodies?” He leans over to Bob's initial drawing and points to the result area to say, “So that's the mechanism in the first part of the window.” He continues, “And then in the other window, it's more like…” but instead of describing this mechanism with words, he uses a representing gesture to describe the two antibodies bound together. He thus uses the same “gesture language” as Karl introduced earlier, but in a new way, to share his ideas about the molecular interactions. In this situation, the gestures take a heavier semiotic load by actually representing the underlying entities at the microlevel to explore their molecular interactions. Then, Hans quickly transforms these ideas represented through gestures (three-dimensional representation) to small drawings in his notebooks (two-dimensional). The final drawing shown in Figure 6 shows that the students ultimately integrated this idea into Bob's original drawing.

In this interaction, they are concerned with exploring how the molecules bind in the control line. This exploration is necessary to extend and finalize their initial drawing. As we saw in the previous episode, this inquiry was triggered by their peers' drawing, which also included a control line and contributed to opening up a new space for exploration. Hans's drawing in this episode, which clearly shows the movement of molecules from the application area to both the test and control line, also points to this “gap” in their understanding. The same pattern in the use of these representations (drawing, deictic gestures, talk, and iconic gestures) is thus visible in this episode.

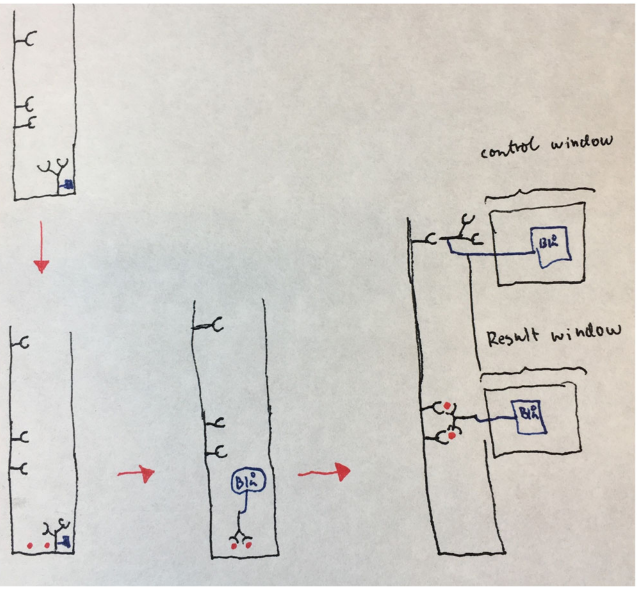


FIGURE 6 The final drawing

This episode demonstrates the students' advanced mechanistic reasoning. As a result of observations from the previous episode, they extended their model to provide the mechanism of the whole pregnancy test, and not only the test line. These two episodes together thus demonstrate the third heuristic, focused on coordinating relationships across the micro/macro level. In this episode, the conversation rapidly moves between observations at the macro level, such as "this is used as a control window." pointing to the control line in the drawing, at the same time they are exploring the underlying molecular interactions. To explore the spatial details of these interactions (heuristic 2B), they rely heavily on representing gestures.

Soon after this episode, they finished their drawing, where we can see that they had extended their original draft to also include the molecular interactions in the control window. Their final drawing also includes arrows to show the overall coherence of their model as a description of different stages in a process, probably because a fourth drawing was introduced that broke the implicit left-right reading.

5 | DISCUSSION AND CONCLUSIONS

In this section, we will summarize and discuss the two major findings in this paper: first, a pattern in the use of drawing, talk, and gestures characterizing the students' model-based reasoning; and second, the semiotic role of the various representations in different phases of the modeling process. Finally, we discuss the implications and limitations of the study and provide suggestions for further research.

5.1 | A pattern in the use of representations characterizing students' model-based reasoning

Modeling is a cyclical process of construction, use, evaluation, and revision (Gilbert & Justi, 2016; Lehrer & Schauble, 2006; Schwarz et al., 2009). In this study, we have shown how the process of drawing-based modeling plays out in naturalistic dialogues with undergraduate biology students in a laboratory context. Several studies have started to reveal the importance and workings of different representations for students' reasoning (Bolger et al. 2012; de Andrade et al., 2021; Knain et al., 2021; Mathayas et al., 2019; Tytler et al., 2020; Wilkerson-Jerde et al., 2014). The contribution of our study is to provide further insight into the roles of drawing, talk, *and* gestures in students' model-based reasoning. We have presented a social-semiotic analysis of students' drawings as well as a detailed analysis of students' interactions after they develop an initial drawing (episode 1), evaluate this drawing (episode 2), and ultimately revise and finalize their drawing (episode 3).

During these three critical episodes in the students' modeling, different student-generated drawings became important meaning-making resources. The drawings seemed to open a creative space for their collective meaning-making, while explorative talk, together with iconic gestures, became an important resource in "filling the gaps" in their model, thus supporting them in developing a disciplinarily accepted explanatory model. This scenario is in line with the findings of Tytler et al. (2020), who showed that drawings can function as proto-models that are emergent and unresolved, and that these proto-models support model-based reasoning.

Throughout the three episodes presented in our study, each of the new drawings (and the semiotic choices made in these drawings) seemed to open new spaces for the students' reasoning. Deictic gestures contributed to focusing on specific details in the drawings, which were explored further through talk and iconic gestures. As the students' meaning-making moved (often rapidly) through the recurring pattern of drawing, deictic gesture, talk, and iconic gesture, their reasoning seemed to become increasingly focused on specific details and to fill the gaps in their mechanistic explanatory model. Indeed, our findings show that the students' mechanistic model-based reasoning (Krist et al., 2019) was characterized by this pattern: both in exploring the underlying entities, properties, and interactions (heuristic 2) and in linking and coordinating how these underlying entities led to the observable phenomenon (heuristic 3).

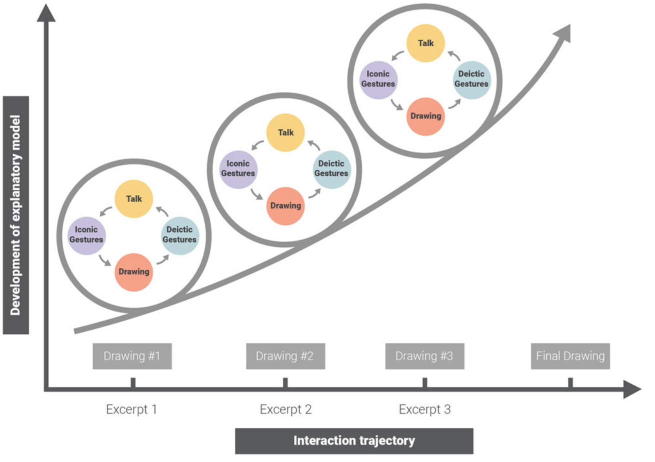


FIGURE 7 Model showing a pattern in the use of the representations (drawing, deictic gestures, talk, and iconic gestures) that characterized the students' model-based reasoning through the cyclical modeling process

We will argue that the nature of the different representations (e.g. drawings, talk, and gestures) contributed to bringing their meaning-making forward. In particular, the combination of the static drawing (a new one for each episode) with the more dynamic and flexible nature of talk and gestures was fruitful for supporting the students through the cyclical modeling process of construction, evaluation, and revision of their model. In this way, the student meaning-making "spiralled" upwards towards a more complete and disciplinarily accepted explanatory model. We have developed a model to illustrate how the pattern in the use of representations contributed to bringing their meaning-making forward and finally towards a disciplinarily accepted explanatory model (see Figure 7). This is not to say that their model developed during every cycle in the pattern. For instance, their reasoning about how the molecules move in the first episode did not lead to the disciplinarily accepted explanation that the molecules move by capillary forces (and not osmolarity, as they suggested). In the first two episodes they explored several ideas related to the molecular mechanism behind the test, related to all three heuristics (Krist et al., 2019). This finding is in line with previous research pointing to an initial phase in the modeling process characterized by "messing about" (Wilkerson-Jerde et al., 2014). Their reasoning became increasingly focused on specific details of the molecular mechanisms in the last episode, however, which is in line with the "digging in" phase previously characterized by Wilkerson-Jerde et al. (2014).

Our findings also show how the different representations were used according to their affordances in bringing the students' meaning-making forward during the modeling process. The pattern described in Figure 7 was repeated rapidly (several times) in all episodes, although the semiotic load that the different representations bore in bringing their explanatory model forward differed slightly in the three episodes. In the first episode, the drawing bore the major semiotic load, while iconic gestures took on a larger semiotic load in the third episode.

We will now discuss the role of the drawing (with a particular focus on the first episode) and the role of the iconic (representational gestures) in the third episode to show how these representations were used according to their affordances, depending on where they were in the modeling process (construction, evaluation, or revision).

5.2 | The critical role of the drawings in students' model-based reasoning

Recently published studies have shown that the development of student-generated drawings can support students' reasoning (de Andrade et al., 2021; Knain et al., 2021; Tytler et al., 2020). Research has also shown that certain semiotic choices in student-generated drawings can support the development of disciplinarily accepted explanations (Tang et al., 2014). The analysis presented in this study showed that the drawing played an important role in displaying spatial relationships, which, combined with other aspects of visual grammar such as layering, framing, and connecting, contributed to telling a rich visual story of how the molecular movement and binding led to the observable blue color in the result window (first episode). de Andrade et al. (2021) found that drawings supported mechanistic reasoning by pushing students to look for a mechanism. Our study provides further insight into how certain semiotic choices made in drawings seemed to open up and allow for students' mechanistic model-based reasoning (Krist et al., 2019). For instance, the combination of a macro/microperspective through layering in the *drawing*, which we may consider to be a way of thinking across scalar levels (Heuristic 1), enabled further reasoning about the relationship between the molecular interactions (microlevel) and the observations of the pregnancy test (Heuristic 3). We may consider such reasoning, focused on how the underlying entities lead to the observed phenomena, as the most advanced level of mechanistic reasoning (Krist et al., 2019).

5.3 | The role of talk together with deictic gestures in students' model-based reasoning

As mentioned above, the combination of the static drawing with the more dynamic and flexible nature of talk and gestures was fruitful for supporting the modeling process. Previous research has shown that moments of talking when looking at representations are moments of significance or potential misunderstanding (Roth & Pozzer-Ardenghi, 2013). Our findings suggest that deictic gestures together with talk have a similar function in students' model-based reasoning. We suggest that their pointing to specific details in the drawing showed what they considered important or what needed further exploration. The use of deictic gestures marks a new cycle through the pattern where new aspects of the drawing (or a new drawing) are explored. What this situation also shows, in line with previous research (Pozzer-Ardenghi & Roth, 2004; Roth & Pozzer-Ardenghi, 2013), is that representations (in this case, the static student-generated drawing) become an important background that supports the reasoning about other aspects that is not directly observable in the representations.

Certain aspects are not easily drawn, such as the process of binding (Tang et al., 2019), and requires a description through other modes of representations. Our analysis shows that talk together with deictic gestures was used to describe such processes (binding), give molecules properties (high affinity), suggest mechanisms for movement (osmolarity), suggest conditional mechanisms that were not drawn (they only moved when they had bound the antigen), and point to incoherence between their model and the observable phenomena ("how does it make a difference?"). Talk together with deictic gestures contributes to the students' model-based reasoning in several ways.

5.4 | The role of talk and iconic gestures in students' model-based reasoning

Talk together with iconic gestures were particularly important in exploring aspects *not* shown in the drawing. For instance, iconic gestures contribute by adding temporal and spatial aspects. In the first episode, when the students were evaluating their first draft, iconic gestures were used to describe the direction of movement and to visually represent the pregnancy test line (which was not presented as a line in the drawing). However, in the third episode, where they are revising (extending) their drawing by exploring the molecular mechanism in the control line, iconic (representing) gestures take on a much heavier semiotic load. Mathayas et al. (2019) suggest that representational gestures can function as an epistemic tool by making underlying mechanisms visible and thus are important in model-based reasoning. This finding has been confirmed in our naturalistic case study as the students used representing gestures to explore the molecular interactions in the control line. In this case, representing gestures appeared to take over the role that drawing had previously played in displaying spatial relationships.

Representational gestures have similar affordances as drawing in showing spatial relationships and can be appropriate in exploring molecular mechanisms, although they can be used in a more dynamic fashion due to their temporal and non-persistent character (Fredlund et al., 2021; Mathayas et al., 2019). This explains why representing gestures played such an important role in exploring molecular interactions not displayed visually.

Previous research has also shown that the use of gestures in science can help students express phenomena when they are not able to express it verbally (Mathayas et al., 2019; Park et al., 2006; Roth & Lawless, 2002a) and can be important in the translation of a spatial model to the verbal mode (Mathayas et al., 2019). Our findings have also shown that representational gestures are important in the other direction: that is, from the verbal mode to a spatial model. For instance, even though the students were able to describe the molecular interactions with words (antibodies binding antibodies), this description would not be easily translatable into drawing, since drawing requires more details about spatial relationships. Our analysis illustrates how the students developed their own gesture language to represent antibodies and antigens with their hands. They used this gesture language to share new ideas about the molecular interactions that they eventually translated into the drawing, which contributed to finalizing their explanatory model. This finding is particularly relevant for students' model-based reasoning, because spatial models have other epistemological commitments than talk, and they require that students decide on spatial relationships and relative size (Fredlund et al., 2021; Kress et al., 2001).

5.5 | Implications, limitations, and further research

With a growing focus on engaging students in scientific practices (American Association for the Advancement of Science, 2011; National Research Council, 2012) such as modeling, there is an increased need for knowledge of how students can be supported in such processes. The insights provided in this paper will be valuable for teachers and for the instructional designs of learning contexts focused on supporting students' model-based reasoning through drawing activities. For instance, our findings have shown how students' model-based reasoning (through explorative talk and iconic gestures) can be supported, but perhaps also hindered, by the semiotic choices made in student-generated drawings. The study provides empirical support for instructional designs focused on the sharing and negotiating of drawings both in small-group settings and in plenary sessions. Our study also confirms the fruitfulness of combining social-semiotic analysis with IA (Knain et al., 2021), as we have shown that this combination can provide new insight into the role of these representations in students' model-based reasoning.

Because the findings presented in this study are based on a case study, they will only support analytical generalizations (Kvale & Brinkmann, 2009; Yin, 2009), and analytical generalizations depend on the ability of the findings to predict what will happen in similar situations (Kvale & Brinkmann, 2009). Does analyses of scientific meaning-making via drawings, talk, and gestures prove fruitful in other contexts—and what variations arise with different science content and across varied populations? Further research would be useful to highlight the limits and the potentials with exploring communication embodiments within scientific modeling and meaning-making.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data are not publicly available due to privacy or ethical restrictions.

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APPENDIX A: TRANSCRIPTION CONVENTIONS

TABLE A1

[]	Start and end points of overlapping speech
(.)	A brief pause, usually less than 2 s
?	Rising pitch or intonation
.	Falling pitch or intonation
((*italic text*))	Description of what happens