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This paper discusses the use of non-verbal representations in a modelling-based science teaching context, in which argumentative and explanatory situations occur. More specifically, we analyse how the students and teacher use representations in their discourse in modelling activities, and we discuss the relationships between the functions of these representations and the demands of the explanatory and argumentative situations that exist in that classroom. The data were collected by video recording all the classes in which a teaching sequence about intermolecular interactions was used—a topic which the students had not previously studied. In the activities, the students had to create, express, test, and discuss models in order to understand the difference between intermolecular and interatomic interactions, as well as their influences on the properties of substances. Initially, we selected excerpts of the recorded classes in which a non-verbal representation was used. Then, we used criteria to identify the argumentative and explanatory situations (previously defined), and we created categories for the functions of the representations that were used in order to analyse all the identified situations. The analysis supports conclusions indicating the relevance of the use of non-verbal representations in the construction, use, and defence of explanations. As the defence of explanations was the main context in which argumentative situations occurred in this study, our conclusions also indicate the contribution that representations make towards changing the status of the students' explanations.

Keywords: *Modelling; Explanation; Argumentation*

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Introduction

In this paper, we study three practices which are inherent to science: representation, argumentation, and explanation. More specifically, we investigate multimodal discourse (i.e. what encompasses various modes of communication, such as gestures, concrete, and verbal representations) in a modelling-based science education context, in which argumentative and explanatory situations occur. Initially, we analyse how the students and the teacher use representations in their discourse. Then, we relate the various functions of these representations to the explanatory and argumentative situations identified in this educational context. The study of these practices is in line with various educational documents that provide guidance for the development of teaching practices (for instance, National Research Council, 2012).

Some authors reinforce the importance of studying multimodal discourse in science and in science education (Adadan, 2013; Ainsworth, 2006; Kozma, 2003; Márquez, Izquierdo, & Espinet, 2003; Waldrip, Prain, & Corolan, 2010) since, in the majority of studies, verbal discourse (oral or written) is prioritised in relation to other modes of communication. In the case of argumentation, for example, Erduran and Jiménez-Aleixandre (2008) affirm that the study of multimodality associated to argumentation is important, since the projects in that area mainly cover only verbal discourse.

In our view, studies on the use of other non-verbal modes of communication associated with arguments and explanations are important. However, in consulting the literature, we did not find a single study in which representations are associated with these two discourse practices. Therefore, with a view to contextualising our work, and to support our definition of explanatory and argumentative situations, we discuss projects which independently address some of the key aspects of explanations, argumentation, and representations in science teaching.

Explanation in Science Education

In analysing the literature, we did not find consensus with regard to the terminology and definition of 'explanation'. Authors use the terms *explanation* (Gilbert, Boulter, & Rutherford, 1998), *scientific explanation* (Nagel, 1961; Norris, Gulbert, Smith, Hakimelahi, & Phillip, 2005), and *explanatory episode* (Kress, Ogborn, & Martins, 1998), but only in this last case a justification is given for the choice of terminology. According to the authors, they did not opt to use explanation or scientific explanation, but instead used the term explanatory episode because it would be difficult to isolate explanatory sentences in discourse.

There is also no agreement among authors regarding a broader definition of explanation. Gilbert et al. (1998) state that a simpler definition would consider an explanation to be the response given to a specific question. Norris et al. (2005), in analysing the work of other researchers, affirm that explanation is an action intended to clarify something or make it more intelligible. According to Braaten and Windschitl (2011), philosophers propose many ways of conceptualising scientific explanations. The authors summarise their main attributes as:

> *covering law*: deductive arguments explaining events as natural, logical results of regularities expressed by laws; *statistical-probabilistic*: induction from a trend or pattern in data (that) may or may not seek underlying causes for events; *causal*: induction from patterns in data but explicitly seek underlying causes for events; *pragmatic*: relies on shared agreement about the 'contrast class' inherent in the why-question: Why is this (and not that) the case?; and *unification*: explanations for singular events are unified into generalizations through use of major theories in science. (Braaten & Windschitl, 2011, pp. 643–644)

Braaten and Windschitl (2011) also affirm that the most frequent models of scientific explanation presented in educational studies are: *explanation as explication*, *explanation as simple causation*, and *explanation as justification*. *Explanations as explications* are those that are strongly descriptive in character, in which the focus is on clarifying terminology and/or meanings, or describing the rationale used to solve a problem. For them, this type of explanation can be very useful, even for researchers, in communicating and clarifying their work to different scientific communities. Nevertheless, when only this type is emphasised in teaching, there seems to be no consideration given to the fact that, in science, explanations should be related to natural phenomena—which involves more than expression of meanings or of strategies for solving problems.

In the *explanation as simple causation* model, the main attribute of an explanation is the establishment of relationships between causes and effects, which can have different levels of complexity. According to Braaten and Windschitl (2011), one of the main difficulties with this model lies in the degree of inference that may be required to establish a relationship between cause and effect in a phenomenon, since it is not always easy—or even possible—to identify and establish causes. Furthermore, the explanation is often presented as the main manner of making sense of phenomena, ignoring other ways such as, for instance, the use of probability and statistics (Braaten & Windschitl, 2011). Such simple causal explanations are indicated as preferable in many science classrooms (Osborne & Patterson, 2011).

In the case of *explanation as justification*, the emphasis is on the construction of arguments. In this situation, students are asked to produce an explanation that follows the pattern 'claim—evidence—reasoning', which is consistent with the construction and analysis of arguments. Braaten and Windschitl (2011) criticise this structure's emphasis on explanation and the use of evidence to justify claims, especially in cases where these claims are more hypothetical or descriptive than explanatory in nature (i.e. involving *how* or *why* in relation to some phenomenon). For these authors, such explanations would be inconsistent with any of the explanatory models in the philosophy of science. Osborne and Patterson (2012) also criticise the use of this structure to refer to an explanation, since to them, the elements cited earlier pertain to an argument. To show this, they quote Toulmin's argumentative model, setting forth its main elements: *data*, *claim*, and *warrant* (Toulmin, 1958), and showing how these can be associated with evidence, claims, and reasoning.

In a paper published some years earlier, Gilbert et al. (1998) present a typology of explanations. Specifically, in relation to science education, they state that the most frequent explanations are:

> *descriptive*: (a response to the question) How does this phenomenon behave?; *causal*: (a response to the question) Why does this phenomenon behave as it does?; and *interpretative*: (a response to the question) Of what is the phenomenon composed? (Gilbert et al., 1998, pp. 85–86)

The authors state that, in an attempt to meet demands from curricula, such explanations are presented to students without further discussion or questioning.

In this section, we show how literature is confusing about the meaning of explanation. By detailing the contributions from two relevant papers in the area, we summarise what is being considered the main attributes of explanation in the science education context. From such attributes, in a following section we define what we assume as an explanatory situation in this study.

Argumentation in Science Education

Recognising that argumentation is an important scientific practice (Berland & Reiser, 2008; Duschl & Kirsten, 2009; Duschl & Osborne, 2002; Mendonça & Justi, 2013a) and advocating for a more authentic teaching of science (i.e. closer to science and therefore fostering a better understanding of science on the part of the students) (Gilbert, 2004), the insertion of this practice into classrooms has been defended by science education researchers (for instance, Berland & Reiser, 2008; Mendonça & Justi, 2013b; Osborne, Erduran, & Simon, 2004).

In teaching situations, the teacher's discourse generally aims to convince students of a consensual scientific view of a phenomenon (or even imposes such a view). Consequently, an opportunity to have a truly dialogic discussion is discouraged, since the students do not have an active voice when relating with the teacher or even to other classmates. This is because interaction between students through group discussion activities is also not encouraged, which is consistent with other situations involving the class as a whole in identifying and evaluating different lines of thinking (Driver, Newton, & Osborne, 2000; Duschl & Osborne, 2002; Mendonça & Justi, 2013b; Osborne & Patterson, 2011). As a result, it is important that students have the opportunity to generate (or be introduced to) competing hypotheses so that they can analyse, discuss, and evaluate them using argumentation. The literature has shown that students' participation in such argumentative activities have contributed to their conceptual development, supporting a clearer understanding of concepts they already have some knowledge of, the production of new concepts, and the modification of alternative conceptions (Cross, Taasoobshirazi, Hendricks, & Hickey, 2008; Mendonça & Justi, 2013b; Passmore & Svoboda, 2012; Uskola, Maguregi, & Jiménez-Aleixandre, 2010; Venville & Dawson, 2010; von Aufschnaiter, Erduran, Osborne, & Simon, 2008). Some of these researchers have attributed such positive results to the fact that teaching which favours student argumentation brings the students an understanding of the reasons that make one model better than another, and to the dialogic nature of teaching.

Considering the possibility that argumentation may emerge from the discussion of different explanations, Osborne and Patterson (2011) defend the importance of the distinction between these practices because, despite the fact that both are related to the search for a better explanation, argumentation and explanation are not equivalent. In the same paper, the authors point to some examples of studies in science education that exhibit some type of confusion when characterising explanation and argument. In one of the studies they critique (Berland & Reiser, 2008), a 'process of constructing and defending explanations' is proposed. This is argumentation involved in practices that propose and evaluate knowledge, since arguments are necessary in justifications and persuasion related to the better explanation. The criticism directed at this study is related to some characteristics of this process of constructing and defending explanations, which according to Osborne and Patterson (2011) are similar to what is proposed for an argument in other well-known literature in the area of argumentation, such as the work of Toulmin (1958).

Regardless of the aspect discussed with relation to the distinction between argumentation and explanation, we can see that literature focuses on these processes when they occur exclusively as a result of verbal communication (oral or written). Along these lines, we consider that discussions about such practices associated with other modes of communication may be relevant in bringing different contributions to the understanding of the roles and demands of these modes in the classroom.

Representation in Science Education

The discourse used in science is characterised by the presence of different representational modes. Researchers share their work with their peers using texts, speech, graphics, diagrams, three-dimensional models, etc. In other words, they use a *multimodal* discourse.

As discourse in science is recognisably multimodal, in the case of chemistry, the use of different resources for communication, whether these resources are connected to verbal discourse (oral and written) or not, is clearly common and necessary. This is due to the subject's strongly abstract nature in comparison with other sciences. Furthermore, just as representations are important to the work of chemists and the development of chemistry, representations are also important in teaching the subject (Adadan, 2013; Gilbert, 2005; Kozma & Russell, 2005).

Recognising the relevance of representations in teaching chemistry, we stress the importance of models, understood here to be partial representations of objects, events, processes, or ideas, produced with a specific purpose (Gilbert, Boulter, & Elmer, 2000). Gilbert et al. (2000) state that models can have a series of functions because they can represent various classes of entities on the macroscopic and submicroscopic levels. Therefore, models can be used to visualise entities, cause-and-effect relationships, and investigations related to a certain phenomenon.

Gilbert (2005) proposes five modes of representation for models; these modes are also composed of sub-modes. They are: *concrete* (*three-dimensional*): representations made of a malleable material; *visual* (*two-dimensional*): drawings, graphs, tables, virtual models, and animations; *symbolic*: symbols, formulae, and chemical and mathematical equations; *verbal* (*oral or written*): description of entities and of the relationships between them in a representation, metaphors, and analogies upon which a model is based; and *gestural*: use of body movements. Research on the use of each of these modes of representation (or combinations of them) has been published mainly in the last decade (e.g. Adadan, 2013; Ainsworth, 2006; Herrera & Riggs, 2013; Padalkar & Ramadas, 2011; Prain, Tytler, & Peterson, 2009; Tang, Chee, & Yeo, 2011). Recently, four edited books (Gilbert & Treagust, 2009; Treagust & Tsui, 2013; Tytler, Prain, Hubber, & Waldrip, 2013; Verschaffel, Corte, de Jong, & Elen, 2010) focus on the role of multiple representations in science education. According to the literature in the area, the expression, the visualisation, the integration, and/or the understanding of either the macroscopic, the symbolic, or the sub-microscopic levels of knowledge can be supported by the use of several modes of representation. They also clearly show that the adequacy of representations varies depending on both the contexts in, and specific purposes for, which they are used.

Recognising the importance of the representational modes presented earlier, we consider activities based on modelling—the process of producing, expressing, testing, evaluating, and modifying models (Justi & Gilbert, 2002)—capable of contributing to student development in relation to creating and understanding the various representations used in science education.

Another possible contribution of modelling activities is that they may promote situations where argumentation occurs (Justi, 2009). This is because students may have to seek out and select data, assess the quality of different information, make decisions (between data or models, for example), justify their claims with evidence, communicate their ideas to their classmates, analyse and evaluate models (their own and others'), etc. From this perspective, Mendonça and Justi (2013b) investigated the relationships between argumentation and modelling based on the implementation of a series of modelling activities. They observed the occurrence of argumentation in all steps of the modelling process experienced by students. Despite the fact that their study focuses on the analysis of verbal argumentation, the authors still conclude that the students' representations are just as important in the argumentative process (to enable the visualisation of some entity) as they are in constructing explanations. The research presented here seeks to deepen such relationships based on analysing the use of representations (expressed in different modes) in argumentative and explanatory discourse that emerge during modelling-based teaching—something that, to the best of our knowledge, is not found in the literature.

Aim

Considering the widespread use of representations in producing and communicating knowledge in science, as well as the fact that students use representations to express and defend their ideas, the need arises to investigate the roles of representations in various classroom practices. As emphasised in the previous section, we did not find studies in science education literature that investigate the use of representations in explanations and argumentation simultaneously. Therefore, our study investigates the following research questions: How do students and the teacher use representations in their discourse in modelling activities? What is the relationship between the functions of such representations and the demand of explanatory and argumentative situations experienced by students and teacher in modelling-based contexts?

Research Methods

Sample and Data Collection

The study was conducted in a class of 38 students (16–18 years old) who were taking evening classes at a public school[1] and were learning about chemical bonding for the first time. These students were accustomed to traditional classes that were basically expositive in nature and focused on the teacher. Therefore, conducting investigative modelling activities and having to discuss their own ideas was something new for the students.

The data used in this study originate from the implementation of a modelling-based teaching unit about intermolecular interactions. The broad aim of this teaching unit is to allow students to differentiate the intensities of interatomic and intermolecular interactions. The unit contains five activities. In the first one, students are asked to predict what would happen when molecular iodine and graphite (compounds that they previously knew to be formed by elements whose atoms tend to be bound by covalent bonds) were heated, to perform the experiment, to compare empirical results with predictions, and to explain the distinct behaviour of both compounds. With such data and information in mind, students are asked (in Activity 2) to produce concrete models that explain their empirical observations in both systems before, during, and after their heating. In order to produce these models, students were provided with several types of materials, such as different sizes of polystyrene balls, modelling clay, sticks, coloured pencils, etc. They have also to draw their models in the worksheet. Therefore, from the reflection about the role played by the energy provided to the systems, Activity 2 aimed at supporting the establishment of relationships between the properties of the substances and the types of bonding in their structures, and the following production and expression of students' models. In the third activity, students perform the reaction between molecular iodine and starch (which produces evidence that, when that substance is heated, there is no breaking of covalent interatomic bonds). In face of the evidence gathered, they are asked to analyse their previous models and, if necessary, to change them so that their model for molecular iodine could explain what they observed in Activities 1 and 3. In Activity 4, students have opportunity to evaluate their current model by applying it in a distinct context: the heating of sugar (assuming to be mainly composed of glucose, a compound that is also molecular). Such an activity may play two distinct roles. If students had produced a model that shows the attenuation of intermolecular interactions of I_2 rather than the breaking of the bond I–I, Activity 4 supports the 'consideration of the scope and limitations' of the iodine model in relation to the sugar model. If not, the new empirical observations become new information about the behaviour of molecular substances, thus supporting the production and expression of a new model. Finally, in the last activity students have the opportunity to discuss about the intensity of intermolecular interactions by explaining why distinct molecular compounds have so different melting and boiling temperatures.

Such a brief description of the teaching activities shows that, apart from the initial activity, all the others require that students established and/or use links between the macro and the sub-microscopic levels, that is, to use visualisation skills. According to the literature on visualisation, this may mean a challenge to many students. So, it is highly likely that, when engaged in such activities, students produce and use multiple representations in order to move between distinct levels of knowledge—as emphasised in many chapters of the book *Multiple representations in chemical education* (Gilbert & Treagust, 2009).

The activities were conducted in six groups of four to six students. At the end of each of them the teacher conducted whole class discussions, when each group communicated and defended its models. The activities required 9 40-minute classes. All classes were recorded using two cameras that were originally placed near two distinct groups (G2 and G3; G4 and G5). Such groups were randomly chosen because the teacher had assured us that, taking into account the students' cognitive level and their general involvement in the classes, there were no significant differences between the groups. Additionally, one of the video cameras was focused on the teacher when she had discussion with one of these groups (either when they requested her presence or when she decided to question those students about a given aspect of their models). As in the first recorded class, we realised that most of the times students from G5 did not speak loudly, one of the cameras was really focused exclusively on G4. So, our final set of data was composed of the discussions occurred between (i) students in groups G2, G3, and G4; (ii) students from these groups and the teacher; and (iii) the teacher and the whole class. In terms of the discussions between students in groups G2 and G3, as there was only one camera recoding them, it was not possible to register all discussions. The research assistant who was recording with this camera tried to move from one group to another when she realised that they were involved in intense discussions (and when such a decision would not interrupt the recording of a current interesting discussion between students from the other group). Therefore, we were not able to register all the dialogues between the students in the class. On the other hand, the discussions between the teacher and the students from G2, G3, G4, and G5 or the whole class were fully recorded. Finally, all 3D and 2D models were photographed after each class. The gestures were also photographed after the teaching process, but with the help of an adolescent who had not participated in it. We opted for this way of showing students' gestures because it would be impossible to use the images from the original videos without showing students' face—which we cannot do for ethical reasons.

Data Analysis

The analysis process can be briefly described in four steps: selection of the data related to the aim of the study; establishment of criteria to determine the argumentative and explanatory situations; creation of categories for the functions of the representations; and use of the categories to analyse the data. The main activities related to each of these are described in the following.

Data selection. First, we watched all the classroom video and the excerpts in which the teacher or students used some type of representation were selected for transcription. The transcription process captured all modes of representation, that is, not only speech (verbal mode), but also gestures (gestural mode), concrete models (concrete mode), drawings (visual mode), and formulae (symbolic mode). Thus, it was possible to visualise the process as a whole, that is, the discourse practices and the use of representations therein. In this article, we present a cross-section of the data that illustrates the main characteristics of the overall results, and which supports the discussion of the questions proposed herein.

Definition of the criteria to identify the situations in which argumentation or explanation occurred between the individuals. This step allowed us to determine, from the transcribed data, which cross-sections involved argumentative or explanatory situations.

We use the term *explanatory situation*, as opposed to simply *explanation*, due to the characteristics of the activities that allowed the students and the teacher to create the explanations, quite often expressed in extensive dialogues. That is, since the activities required the students, working in groups, to produce models, various discussions took place among these groups and between them and the teacher. The explanations were constructed within these dialogues (and not in a direct 'question—response/explanation' process). Along these same lines, we were not concerned with identifying an *argument*, but instead *argumentative situations*, and with investigating how the students used the representations in these situations.

Explanatory situation. In the educational context, explanations differ from those used in the scientific environment, since they are consistent with the curricular models[2] that the students ought to learn at a certain level of education. In our definition of an explanatory situation, we took into account the attributes of the types of explanation commonly used in science education (identified by Braaten & Windschitl, 2011; Gilbert et al., 1998) that are specific to our study due to the nature of our data (gathered in a modelling-based teaching context). Therefore, we identified a situation as explanatory when students:

- define some terminology or meaning;
- describe their reasoning;
- describe a model (or parts of a model) produced by the group and clarified some characteristics of the model for other classmates or the teacher; and
- use the models to establish cause-and-effect relationships between entities or ideas related to the phenomena that they were modelling.

Finally, another characteristic of explanations that is important to the analysis is the creation of questions that generate explanations. In the case of questions, we recognise that, in general, explanations are created when someone requests them (Gilbert et al., 1998). Therefore, the four previous criteria were identified in situations that may have been generated by one or several questions (by both the students and the teacher).

Argumentative situation. In this paper, we have opted to use the term *argument* when referring to the construct presented to defend a point of view, which is made up of a claim supported by the use of evidence and justifications (Erduran & Jiménez-Aleixandre, 2008). Furthermore, the arguments constructed by the students who participated in our study do not always agree with current scientific knowledge, and do not exhibit the same degree of complexity. As with the explanations, the arguments made in the classroom are in line with the curricular models for each educational level.

Considering the context of modelling activities, arguments should be made with the aim of defending or criticising a certain model. In this case, evidence used in the arguments should be data (provided to the students, observed in experiments, or derived from prior knowledge) that are compatible with the model. The justifications should show relationships between such evidence and the student's prior knowledge used to produce the model (Mendonça & Justi, 2014).

In the situations from which we collected our data, the student seeks consensus through arguing with the teacher (T) who, by participating in discussions with students, seeks to help them without directly exposing them to the curricular model. Two types of situations were observed. In the first one, the student has doubts related to two models and should choose one after discussing them with the teacher. In the second situation, the student is unsure whether or not to accept a model and engages in an argumentative situation with the teacher in order to decide. Therefore, by promoting argumentative situations, the teacher should help the students so that they themselves can arrive at a model that is as close as possible to the curricular model. In order to help students decide between two models, for example, the teacher participates in an argumentative situation by criticising and questioning the students, while they defend their proposals. In this process, the individuals can present evidence and justifications that are consistent with their point of view in order to criticise or defend a model. They can even be persuaded to change their stance. In the case of modelling, this means abandoning or reformulating the models that they deem inconsistent.

Another specific characteristic of the discussions during the modelling activities is the possibility that the argumentative situations could revolve around the codes of representation used by the students in their models, or the materials used to build them. This is because there may be a disagreement among the students in the group with regard to the advantages or disadvantages of representing a phenomenon in a certain manner. They might also disagree about the coherence between the codes used and the conceptual aspects that are to be represented.

In relating argumentation to explanations, Berland and Reiser (2008) affirm that argumentation may occur in proposing and criticising knowledge, since justifications and persuasion are both necessary to obtain a good explanation. Agreeing with this idea, in this study we admit that argumentation related to different explanations may occur with the aim of attaining an explanation that is better suited to a certain context.

Finally, we emphasise that we were not concerned with evaluating if the students' arguments were totally in line with the curricular model in regard to conceptual aspects. This is because students may not have all the previous knowledge required, or this knowledge may be inconsistent with constructing a model appropriate for the curriculum at the time of the activity. However, the student can construct a model that is consistent with the knowledge that he or she has at that initial moment. Nevertheless, as the activities are undertaken, we expect that the students would improve their knowledge with regard to conceptual aspects as a result of the data provided in the activities, the expression of the models, the presentation and explanation of the models to the class, and the discussion of the models in groups and with the teacher. As a consequence, they will be able to choose the most relevant model.[3]

Creation of categories for the functions of representations. The data obtained from the first two steps were analysed in order to identify the functions of the representations in the individuals' discourse. This analysis gave rise to the categories that summarise all the functions identified in the selected video excerpts.

Use of the categories to analyse the data. After the creation of the categories, each of us reread the transcription of the argumentative and explanatory situations in order to categorise parts of the dialogues according to the categories. This resulted in tables similar to those exemplified in the next section. Then, we analysed each situation trying to discuss our research questions, that is, to understand the meaning of the use of the representations, and to establish relationships between the functions of such representations and the demand of the situations experienced by the students and the teacher. During this process, we recognised the need to identify the frequency of the occurrence of each function. Then, we retook the whole set of data and counted:

- the occurrence of each function of the representations used by the students and the teacher in each type of discursive situation. This means that each time a representation was used with a given function, it was counted. So, if a given representation were used twice with the same function during a specific situation, it was counted two times; and
- the occurrence of each mode of representation in such situations. So, if a given mode of representation were used with the same function in a given situation, it was counted only once. In particular, as the students and teacher have spoken almost all the time, the verbal mode was acknowledged as a mode of representation

only in the occasions in which students expressed their models using only words, without the help of any other mode of representation (concrete, drawings, symbols, and/or gestures), that is, only when it was exclusively used.

As we had not been able to record all the dialogues between students in some groups, the results of the counting process do not represent the totality of the occurrence of each function and mode of representation. However, as most of the dialogues occurred during the lessons were recorded, we assume that such results are representative of the whole. Even assuming this limitation, the results of the counting process allowed us to broaden the discussion of our results.

The phases of 'defining the criteria to identify the situations where argumentation or explanation occur among the individuals', and 'creating categories for the functions of the representations' were independently conducted by three researchers (the authors of this paper). The results of the individual analyses were discussed, and the divergent points that arose were discussed until a consensus was reached. The phase 'using categories to analyse the data' was also independently conducted by the three of us. Inter-rater reliability of 93% was achieved (Cohen, Manion, & Morrison, 2011). We view this high value as a consequence of the intense discussions that occurred during the creation of the categories, which resulted in a clear understanding of them. All coding inconsistencies were discussed and negotiated until a final agreement was reached between us.

Results and Discussion

The process of watching the class videos allowed us to identify all the different uses of the representations by the students and the teacher during the dialogues. From this identification, we systemised these uses as a set of categories. They are characterised in the next sub-section.

In order to provide the reader with an overview of the data and to support her/his understanding of the analysis, we present two tables that explain the following: the discourse situation (argumentative or explanatory), the dialogues between individuals in the group and with the teacher, the representation used by the individual, and the function of the representation. In Tables 1 and 2, each line contains an event related to the use of a given representation. As many times a given representation based distinct events, it was repeated in the table so that the reader do not have to return to previous lines to understand that event. The events were numbered in order to facilitate reference to specific examples.

Before presenting the dialogue, we characterise the excerpt to facilitate the reader's understanding of the context in which it occurred. Excerpts where we were unable to understand the students' speech were marked with the symbol (?). Excerpts we considered irrelevant to understanding the context and data analysis were edited and the removed speech was marked with the symbol (…).

In presenting the dialogue, the students are identified by the code SX, where X is a random number identifying the student, while the teacher is identified by the letter

T. When several students say the same thing together, we use the code Ss. The models are referred to using the code $MZ_{substance}$, where Z is a number identifying the model, followed by the name of the substance the model represents (e.g. $M1_{iodine}$ refers to the group's first model for iodine).

The whole set of data is composed of argumentative and explanatory situations involving: only students of a given group, the teacher and the students of a given group, and the teacher and the whole class. Therefore, the duration of the situations varied a lot. In this paper, we present a dialogue between a group of students and the teacher as an example that illustrates the data used and the way in which the complete study was analysed. This dialogue was chosen because it (i) contains explanatory and argumentative situations and (ii) allows the identification of almost all the functions of the representations in the discursive situations. For clarity, we separated the dialogue into two parts: Table 1 presents the explanatory situation, whereas Table 2 shows the argumentative situation. However, we must emphasise that the dialogue occurred sequentially, with no temporal interruption, for 8 minutes and 40 seconds.

The System of Categories

The categories we create to analyse the functions of the representations in the teacher and students' discourse in a modelling-based teaching context are:

1. *To reinforce what the individual is expressing orally*. Situations in which the individual relies on the representations to reinforce something that he is saying. In general, his speech could be understood without the representation, but this understanding tends to be facilitated by the use of the representation. The subjects may use this tool because they believe that it allows them to express their ideas more clearly, or even to emphasise a specific aspect of their ideas. Examples: events 3, 7, 8, 10, 11, and 12 in Table 1; events 17 and 18 in Table 2.
2. *To substitute specific scientific vocabulary*. Situations in which the students use a representation to substitute for a specific scientific term. Sometimes, the representation is used along with another everyday term. This may occur when they do not know or have forgotten the appropriate scientific term referring to a process, phenomenon, or entity they have already studied (event 6 in Table 1), or when they do not yet feel sure about using a certain vocabulary term (events 15 and 19 in Table 2). In the case of the teacher, this situation can occur when she considers it simpler to not use specific vocabulary in order to facilitate student understanding (event 4 in Table 1).
3. *To present the model showing the information that supports a proposal*. Situations in which the students express their ideas through a model produced from a question arising from an activity or a (direct or indirect) request from the teacher to reformulate a previous model. This category includes those situations when students are presenting their models in a general manner, in other words, when they have just created or re-created their model (event 9 in Table 1). This category does not include the teacher directly because she produces models with other aims (such

as representing an idea from the students in order to better understand them, clearing up questions about more abstract concepts, etc.).

4. *To check understanding of a representation or a response, presenting the representation once again or stressing an aspect implicit in the group's presentation of the model*. This category can be identified when the individual (i) uses a representation with the aim of confirming his or her understanding of something another individual expressed (events 1 and 11 in Table 1) or (ii) selects a specific aspect of the presentation of an idea which was not well understood or which was implied, and makes use of the representation to try to understand this aspect (no example in Tables 1 and 2, only in some of the other 21 discursive situations analysed in the complete study). These situations can occur, for example, when the teacher wants to confirm that she understands an idea that the students have expressed or vice versa (events 4, 7, and 13 in Table 1; events 16, 17, and 18 in Table 2).
5. *To explain a concept or specific aspect*. This occurs in situations in which the individual uses a representation to give an explanation about some concept or specific aspect (events 8 and 12 in Table 1). Also included in this category are those excerpts of the dialogue where one individual responds to another about a certain aspect of the representation he or she had doubts about, or about an implied aspect (event 19 in Table 2). Generally, the teacher uses this when she deems it necessary to fall back on the representation as a tool to facilitate dialogue with the students (events 1 and 2 in Table 1). However, this can also take place with the students using a representation with the same aims, since at times they may not be able to make themselves understood without the use of an extra tool besides speech (events 3, 6, and 10 in Table 1; events 15 and 18 in Table 2).
6. *To show inconsistency in the representation and a better way of representing it*. This situation is identified when the representation is used to prove some inconsistent aspect within it, or in another representation to which it is related. This inconsistency often relates to the use of representation codes which conflict with some concept involved in the representation. Generally, at the same time that this aspect is highlighted, the representation that would be more coherent (or appropriate) is shown. There are no example in Tables 1 and 2, but we discuss one from another situation in a following section.
7. *To make reference to a representation of interest*. Situations in which the individual simply points to a representation he or she mentions in a dialogue, instead of an explicit reference to what is being represented (events 5 and 14 in Table 1; event 19 in Table 2).

Dialogue Between the Teacher and a Group While Conducting an Activity

This dialogue took place while the students were constructing models to explain the behaviour of iodine and graphite before, during, and after these materials are heated. Before the activity, the students had made predictions about what would occur. Then, they conducted the experiments and observed the results, and discussed the transformations they observed. Since the activity had already begun, the teacher approached the group to check progress, and the students took advantage of the opportunity to ask questions about the formulae for iodine and for graphite. At that point, the dialogue presented in Table 1 began. In talking with the students, the teacher used concrete models to question them (events 5, 7, and 14). The students used gestures at times when they were having difficulties expressing themselves (events 3, 10, 11, and 12)—something frequently reported in the literature (Goldin-Meadow, 1999; Goldin-Meadow & Alibali, 2013; Herrera & Riggs, 2013; Padalkar & Ramadas, 2011). Sometimes, these gestures were not essential to understanding the excerpt since their ideas were easily understood through speech alone. Nevertheless, the fact that the students made the gestures indicates that they were important to them as a support, or reinforcement, for what they were saying. So, independently of the gestures had been made intentionally or not, what is important in this study is that they had a clear function in the discursive situations. At the end of the excerpt, upon explaining their models (event 16), the students insisted in the belief that covalent bonds are broken during the fusion of iodine, although the teacher had asked questions that favoured reasoning in terms of intermolecular interactions. The discussion (finished in Table 2) ended when the bell rang to signal the end of class.

The explanatory situation presented in Table 1 initiates when S2 expressed doubts about the formula for graphite, which the teacher tried to resolve by affirming that this was represented by 'C' and not 'C_2' (*to explain*). She also reminded them of the formula for iodine (I_2) and that the chemical bonds in both substances were covalent (*to explain*)—aspects that they had previously studied (events 1 and 2). As the students seemed to still have some doubts about the meaning of graphite's formula being 'C' (since the group presented a model with a ball representing the graphite, Figure 2), the teacher requested the students to explain how melting occurs in any material. The students responded using gestures (*to explain* and *to reinforce speech*) and the teacher used this response to question the group about the graphite model (*to make reference to*) (events 3 and 4). The teacher's questioning led the students to present, for a second time, the model they had previously made for graphite using two balls (Figure 3) and to show how the model explained the high melting temperature for graphite (*to explain* and *to substitute vocabulary*) (events 5 and 6). The teacher then questioned the group about a specific part of the model for graphite (*to check understanding* and *to reinforce speech*) (event 7). In their response, S1 and S2 modified and used the new model (Figure 6, event 8), but did not recognise that it had been modified (*to present the model*) (event 9). The teacher requested more clarification about the graphite, and the students used gestures to respond to the teacher (*to explain* and *to reinforce speech*) (event 10). Next, S2 asked a question about the interaction (attraction and repulsion) between atoms in general, gesticulating while talking (*to check understanding* and *to reinforce speech*). In her explanation to the students, the teacher established a causal relationship between the formation of the covalent bond and the attraction between the nucleus and the electron (event 11). As the students seemed to have understood, the teacher continued, reviewing the models for graphite and iodine with the participation of the group. Through her questions, the students

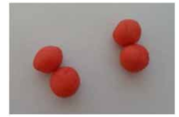
Table 1. Dialogue between teacher and students—explanatory situation

Event	Dialogue	Representation used	Function of the representation
1	T: *The formula for graphite …* Ss: *Is what?* T: *It's C. The formula for graphite is C.* (to explain) S2: *Not two? Just C?* (to check understanding) Ss: *Just one?* (The students thought the formula for graphite would be C_2.) T: *The formula is C!* (to explain) *What type of bond do iodine and graphite make?*	Symbolic: C	To explain To check understanding
2	(…) T: *It's a covalent bond. Both form a covalent bond, ok? All right, I represent iodine with I_2 and graphite with C.* (to explain) S2: *Just C?* T: *The formula for it is C.* (to explain) *Now, since I will represent this in a model that is in line with the facts from the experiment, what does my model have to explain?* S1: *You have to have the before, the during, and the after.*	Symbolic: C; I_2	To explain
3	(…) T: *So graphite is made up of one carbon atom?* S2: *Just one atom?* T: *No, I'm asking you.* S2: *I want to know too.* T: *What happens during melting?* S2: *Nothing. Graphite melting?* T: *No, during the melting of any material.* S2: *They tend to separate. The particles …* [S2 gesticulates, miming a separation, Figure 1. (to explain and to reinforce speech)]	 Figure 1. Gestures showing separation	To explain To reinforce speech

4	T: *What are you going to separate? If there's only one here.* [Teacher points to the group's model, Figure 2. (to check understanding and to substitute vocabulary)] SS and S1: *There are two.* T: *Are there two?* S2: *I don't know.* S1: *Let's assume there are two.* T: *Then let's think. Let's assume there are two, so that means that …* S3: *Graphite won't separate.* T: *And why not? And why does this model …* S3 and S2: *Because the melting temperature is really high.*	 Figure 2. $M2_{graphite}$	To check understanding To substitute vocabulary
5	T: *How does this model here justify the melting temperature?* [Teacher points to the model for graphite, Figure 3. (to make reference to)]	 Figure 3. $M1_{graphite}$	To make reference to
6	S1: *Because it's together before and after.* S2: *Because they're well connected, they're well …* [S2 gesticulates showing union, Figure 4. (to explain and to substitute vocabulary)]	 Figure 4. Gestures showing union	To explain To substitute vocabulary

(*Continued*)

Table 1. Continued

Event	Dialogue	Representation used	Function of the representation
7	T: *So you believe that graphite is like this, made up of groups of two?* [Teacher demonstrates on the model, Figure 5. (to check understanding and to reinforce speech)] *Like this?*	 Figure 5. Model for graphite as interpreted by the teacher	To check understanding To reinforce speech
8	S2: *No, there are several.* [S2 modifies the model, Figure 6. (to explain and to reinforce speech)] *Because they won't separate.* T: *But then, are they all together? Or are they in groups of two?* S1: *No, it's all together.* S2: *I think it's all together.* [S2 changes the model to show the teacher, but we could not see her action. (to explain and to reinforce speech)] T: *So the graphite … Hey, you're changing the model!*	 Figure 6. $M3_{graphite}$	To explain To reinforce speech
9	S3: *No, it's just so we can see … Because …* [S3 takes a pair of balls from the model, Figure 3] *Because if it is two, it's just one thing, none of the two separated … It's like this in the beginning, it's the same thing during, and it's the same thing at the end.* [While speaking, the student shows the model, Figure 3. (to present the model)] T: *But that is what I want to know. How is it in the solid state?*	 Figure 3. $M1_{graphite}$	To present the model
10	G: *Together.* [S1 and S2 gesticulate, trying to show proximity, Figure 4. (to explain and to reinforce speech)] S1: *The organisation.* T: *Ah okay! So, each ball represents what?* S2: *The atom.* (?) T: *So, in the solid state, I have several carbon atoms.*	 Figure 4. Gestures showing union	To explain To reinforce speech

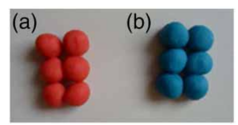
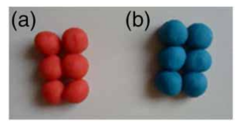
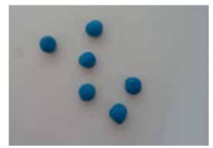
11	S2: *But didn't you say that, if the atoms were equal, they wouldn't repel each other?* [S2 gesticulates, trying to show repulsion, Figure 1. (to check understanding and to reinforce speech)] T: *No, no, look: chemical bonding takes place through attraction, in this case sharing, through the attraction between the nucleus of one atom and the electrons of another.* S3: *Oh okay!*	 Figure 1. Gestures showing separation	To check understanding To reinforce speech
12	T: *The drawing doesn't show this, but it has to be clear, okay? So, now we've moved on to say that, in graphite, carbon atoms … . How many? Is there a defined number?* S3: *No.* S1: *Several.* T: *Several carbon atoms are …* S1: *Interconnected, organised, and really together.* T: *And during heating? Nothing changes, why?* S1: *Because you need more energy to break the attraction* [S1 gesticulates, trying to show breaking the bonds, Figure 1. (to explain and to reinforce speech)]	 Figure 1. Gestures showing separation	To explain To reinforce speech
13	T: *Okay, to break the attraction between them. Okay! And I_2, what is that like?* (to check understanding) S3: (?). T: *Okay, it is made up of iodine. The formula for it is I_2.*	Symbolic: I_2.	To check understanding
14	S1: (?). *But there are several here.* T: *Ah! Okay, put several there for me to see. Is this here the solid? How is this model different from this one? Remembering that the substance represented by this model is melted, is this one melt too?* [Teacher indicates the two models made by the group, Figure 7. (to make reference to)] S1: *This one here is less connected.* [S1 points to the model for iodine, the blue representation in Figure 8. (to make reference to)]	 Figure 7. (a) M3$_{graphite}$ (b) M3$_{iodine}$	To make reference to

Table 2. Dialogue between teacher and students—argumentative situation

Event	Dialogue	Representation used	Function of the representation
15	T: *But I don't see that!* S2: *Maybe it's like this.* [S1 and S3 modify the iodine model, Figure 8. (to explain and to substitute vocabulary)]	 Figure 8. $M4_{iodine}$	To explain To substitute vocabulary
16	T: *Okay! Then let me ask you something: each little ball is an iodine atom, right?* G: [Students agree.] T: *What is different between them?* [Teacher points at the models for graphite and iodine, Figure 7. (to check understanding)] *Is the attraction the same?* S1: *It's less.* T: *The attraction between these two here is the same as between those over there?* [It's not possible to see what she is pointing to.]	 Figure 7. (a) $M3_{graphite}$ (b) $M3_{iodine}$	To check understanding

17	S1: *It is.* (?) [S1 speaks and demonstrates on the model, but it is not possible to understand what she is saying, Figure 8.] T: *Because the attraction will be …* S3: *It will be different.* T: *Different, but will it be greater or lesser?* G: *Lesser.* T: *So, the idea is that, even in the solid state, these groups are more apart.* [Teacher demonstrates on the model for iodine, Figure 6. (to check understanding and to reinforce speech)] G: [Students agree]	 Figure 8. $M4_{\text{iodine}}$	To check understanding To reinforce speech
18	T: *Then let's suppose that this one here is the solid. And for the liquid, what will happen?* SS: *They'll separate.* T: *What will separate?* S3: *These bonds.* [Students show on the model, separating the balls more, Figure 8. (to explain and to reinforce speech)] *Because they will lose attraction.* T: *So, when it moves from solid to liquid, not only will the groups move apart, but the group itself will come apart. Is this what you think?* [Teacher demonstrates on the model, Figure 9. (to check understanding and to reinforce speech)] G: [Students agree]	 Figure 9. $M4_{\text{liquid iodine}}$	To explain To reinforce speech To check understanding

(*Continued*)

Table 2. Continued

Event	Dialogue	Representation used	Function of the representation
19	T: *What type of bond do we have here in both cases?* G: *Covalent*. *T: Covalent! And how does the covalent bond take place?* S1: *A negative and a positive …* T: [Answers no by shaking head]. S2 and S1: *Nucleus and electron?* T: *Sharing of electrons. So, the type of bond that takes place here is the same type of bond that occurs here*. [Teacher demonstrates on the models, Figures 6 and 8. (to make reference to)] S1: *It is, it's just less here.* [S1 points to the iodine model, Figure 8. (to make reference to)] T: *But the bond is the same?* G: *Yes, it's the same*. T: *Then my question for you to consider: why does it separate here but it doesn't separate here?* [Teacher points to the models, Figures 8 and 6. (to make reference to)] S2: *Because the melting temperature for this one is higher, isn't it?* [S2 points to the model for graphite, Figure 6. (to make reference to)] T: *But the greater melting temperature is because of the model?* S3: *Because the attraction is greater, isn't it?* T: *But why is the attraction here greater if the type of bond here and here is the same?* [Teacher asks, pointing to the models, Figures 6 and 8. (to make reference to)] S1: *Because they're … different things*. S2: *Because they're really together, well organised* [S2 shows the model for graphite, Figure 7. (to explain and to substitute vocabulary)] *And there they're not, they're already farther apart* [S2 points to the model for iodine, Figure 8. (to explain and to substitute vocabulary)] T: *Okay, that answers the question. But, I wanted to know about the behaviour during melting. We'll think about that later.*	Gesture: gesture of shaking head to indicate 'no'.  Figure 6. $M3_{graphite}$  Figure 8. $M4_{iodine}$	To make reference to To explain To substitute vocabulary

established a causal relationship using the model (event 12). When questioned about the graphite model, they stated that, in this model, the atoms were interconnected, organised, and very close together, which was why more energy was required (compared to that needed to melt iodine) to break the attraction between these atoms (*to explain* and *to reinforce speech*) (event 12). So, through the teacher's questions, the students established a causal relationship in this event. Next, the teacher asked the group to explain the difference between the models, since they appeared to be similar (Figure 7, event 14) (*to make reference to*). S1 responded (*to make reference to*), but the teacher stated that the group's model for iodine was not consistent with what the student had described (event 15). In this way, an argumentative situation began, and this is described in the continuation of the dialogue (Table 2).

The argumentative situation began with the modification of the iodine model (*to explain* and *to substitute the vocabulary*, Figure 8) by student S2, in trying to make it correspond to what S1 had said during the final moments of the explanatory situation (events 14 and 15). The teacher then started a discussion with the group: first, regarding the difference in attraction between the substances represented in the models (*to check understanding* and *to reinforce speech*) (event 16), and second, about how this attraction was related to the changes in iodine's physical state, and about the model for iodine (*to explain* and *to reinforce speech*) (events 17 and 18). This discussion seemed to have been intentionally instigated by the teacher in order to facilitate the next question, which was the focus of the argumentative situation. She questioned the group about the fact that the students agreed with the existence of the same type of bond in iodine and in graphite, while the proposed models differed with regard to this aspect (*to make reference to*) (event 19). The students had difficulties responding to the teacher and using their ideas around this question to modify the model. For example, at a particular moment, they confused the relation between the phenomenon of melting and the model (*to make reference to*) (event 19). In this way, instead of affirming that the graphite particles did not separate because the attraction between them is very intense (cause) and, therefore, the melting temperature is high (effect), S2 inverted the causal relationship and stated that separation of the graphite particles in the model did not occur because the melting temperature was higher. The teacher questioned the group about this inversion, but the students continued to have difficulty (*to make reference to*) (event 19). The class ended before the teacher could continue the discussion with the students. The discussion continued in the following class, when the students still exhibited difficulties understanding the constitution of the substances. Only after a few classes and several discussions with the teacher were they able to produce models that were consistent with the curricular model.

As explained in the research methods section, after analysing the data, we counted both the occurrence of each function of the representations used by the students and the teacher in each type of discursive situation, and the occurrence of each mode of representation in such situations. In all, 9 argumentative situations and 14 explanatory situations took place. In addition, we analysed the frequency with which the teacher and the students used the representations according to the identified functions. The number of times that the teacher and the students referred to the representations did not differ greatly: 92 and 103 times, respectively. However, the functions for which the representations were used differed. We also analysed the relationship between the functions of the representations and the discursive situation—explanatory or argumentative—in which they were used.

The Functions of the Representations

Table 3 shows the summary of the results related to the functions of the representations used by the students and by the teacher in their discourse.

The function *to reinforce what the individual is expressing orally* was used similarly by the teacher and the students (14 and 17 times, respectively). On the other hand, the function *to substitute specific scientific vocabulary* was used much more by the students than the teacher (20 and 8 times, respectively). We believe that this difference is due to the fact that the students had difficulties with the meaning of some specific terms, such as ‘atom’, ‘substance’, and especially, ‘molecule’. In this case, the dialogues indicate that the students had difficulties related to the topic of covalent bonding (which had previously been taught through traditional teaching methods). Such difficulties were visible, for example, in a dialogue in which two students had trouble with the terms atom and molecule (the students used the terms ‘couples’ and ‘pairs’ to refer to what was an iodine molecule). In the case of the teacher, the times when she did not use the more appropriate scientific terms were when she was seeking to maintain communication with the students to continue the dialogue (which would have been made impossible by introducing a scientific term that had no meaning to the students at that time or that would reinforce a non-acceptable idea (as in event 7)). As a result, the non-utilisation of scientific terms enabled the students to understand the teacher’s explanations and questions.

With respect to the other functions, only the students used *to present the model showing the information in a proposal*. This was expected since the aim of the activity was for the groups to create and express models of the phenomena observed in the experiments—which the teacher did not have to do at any time.

Table 3. Frequency of representation use by the individuals

	Number of uses	
Function	Teacher	Students
To reinforce speech	14	17
To substitute vocabulary	8	20
To present the model	0	21
To check understanding	34	7
To explain	20	32
To identify/to correct	2	0
To make reference to	14	6
Total	92	103

The function *to check understanding of a representation or response, presenting the representation again or highlighting an aspect implicit in the presentation of the model* was used much more frequently by the teacher than by the students (34 and 7 times, respectively). This result is also in line with what was expected (according to the aims of the activities) since the teacher could express questions about the students' proposals or could question some aspects of their proposals. Therefore, the students could identify flaws, not only in their models, but also in their understanding of conceptual aspects (manifested in their representations). In this way, the students themselves could reformulate their models and have a more coherent understanding of the conceptual aspects involved in producing the models. Most of the times when the students used the representations in order to check understanding, the teacher had given some explanation about the conceptual aspects related to the models, and they were seeking to confirm that they had indeed understood what the teacher had explained. We stress that the use of representations for this purpose by the students could have been more frequent if they had had more disagreements among themselves during group discussions. However, as the analysed situation was only the second time that the students had participated in modelling activities and had the opportunity to express and discuss their own ideas, it was not a simple task for them to produce more than one model in the group—which could have led to more questions among the group members as well as the use of models to *check understanding*.

The frequency with which the teacher used the representations in order *to explain a concept or a specific aspect* was less than that of the students (20 and 32 times, respectively). We view this as a consequence of the fact that it was easier for the teacher to express herself orally without the need to rely on other means of communication when explaining something. By contrast, the fact that she used distinct representations in her speech is positive. This demonstrates that she has greater mastery of different representational modes, which facilitates her communication with the students during the teaching process, just as she can use different representations according to students' needs. On the other hand, the students did not have this same facility, which is consistent with the fact that they more frequently used the representations to *substitute specific vocabulary* (as discussed previously). This corroborates Gilbert's statement (2005) that the use of various representational modes and sub-modes is important in teaching. Our results show how important the models were to the students' ability to express themselves. Furthermore, as the teacher several times sought clarification about aspects referring to the group's models (*to check understanding*), it seems consistent that the students used the representations more frequently to explain them to the teacher.

The function *to show incoherence in the representation and a better way of representing it* was used only twice, by the teacher. This makes sense, as the teacher has greater conceptual knowledge to identify and correct the possible inconsistencies in the codes of representation used by the students. The dialogue selected for this paper does not demonstrate this function, but we consider it a relevant one to discuss due to its importance. In this case, the group presented a model for iodine molecules (Figure 10(a)), albeit an inappropriate model. The students proposed two different ways to represent the same entity (the iodine atom, using small red and blue balls). The teacher then proposed the reformulation of the concrete model (Figure 10(b)) and also used representations of the symbolic mode (the formulae for iodine, I_2, and graphite, C) to help the group reformulate the model. Furthermore, the fact that this type of inconsistency rarely occurred indicates that the students adapted well to the modelling activities, even though this had been only their second experience with this type of activity. In other words, this indicates that the students had learnt to properly select and use distinct modes of representation depending on the purpose of their representations.

Finally, the function *to make reference to a representation of interest* was more recurrent for the teacher than for the students (14 and 6 times, respectively). We believe that the teacher used this function more because of her ability to simply point to the model (as a way to catch and focus students attention) and to express her doubts orally, without significant dependence on the model for other objectives (e.g. to *explain a conceptual aspect expressed in the representation*). On the other hand, the students, who were building their knowledge of the abstract concepts involved in the topic under discussion, were more dependent on the representations. This means that they pointed to a model not just as a way to identify their current focus of interest (to make reference to), but also with other aims such as *to explain, to check understanding, to substitute specific vocabulary*, etc. In this case, we confirmed what is expressed in some studies (for instance, Adadan, 2013; Gilbert, 2005; Kozma & Russell, 2005) about the need to use different resources for communication in science education, especially in the case of chemistry, a science that is naturally strongly abstract when compared to other sciences and whose understanding requires students to constantly move between macroscopic and sub-microscopic levels of knowledge.

To complete our analysis, Table 4 presents the frequency of use for the different representational modes. It was created in order to support the analysis of how the modes were used, as well as the relationship between these modes and the demands of discourse situations.

In general, the students used the concrete, visual, and symbolic modes most frequently. This result corroborates the affirmation by Gilbert (2005) that these are the modes predominantly used in chemistry. Therefore, using them and transposing one mode onto another and onto its sub-modes is essential to learning this science. They also use the visual and gestural modes with the same frequency. It seems that the use of the gestural mode emerged directly from the students' need to express themselves in some other non-verbal manner. This is because, unlike the concrete and visual modes which were required in the activities (building a concrete model and drawing),

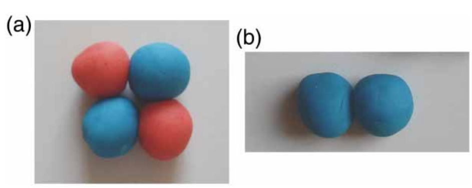


Figure 10. (a) M_{iodine} made by the students; (b) M_{iodine} made by the teacher [here]

Table 4. Frequency of use of different representational modes

Situation	Individual	Mode					
		Concrete	Visual	Verbal	Gestural	Symbolic	Total
Argumentative	Teacher	22	10	0	0	4	36
	Student	13	4	2	1	4	24
Explanatory	Teacher	19	4	0	1	16	40
	Student	34	4	1	8	6	53
Total		88	22	3	10	30	153

the gestural mode was not explicitly requested at any time. In other words, it seems that they felt the need to complement these modes with gestures (used in daily life) in order to be better understood by the teacher, or so that they could more clearly express what the other modes communicated (Goldin-Meadow & Alibali, 2013). According to Goldin-Meadow (2011), in such an integration between gesture and other models of representation (mainly the verbal one), the two of them contribute to convey the meaning to be expressed since they may display distinct (types of) thoughts, thus reducing students' cognitive effort. It is also possible that students gestured in order to link their mental models to phenomena (Padalkar & Ramadas, 2011), which means that gestures can also play a relevant role in reasoning and thinking (Goldin-Meadow, 2006; Goldin-Meadow & Alibali, 2013; Herrera & Riggs, 2013).

Another interesting result is the fact that the students used the symbolic and visual modes less often than the teacher did. This may be due to the need for a greater level of abstraction needed to express oneself using the symbolic mode, and the students' difficulty in expressing themselves through a drawing, compared to their facility in creating a model in the concrete mode. Other possible explanations for the teacher's more frequent use of the visual mode could be: greater capacity to draw (instead of building concrete models) at some points in the discussion, and the fact that many of the discussions occurred as a result of a drawing initially made by the students. In this last case, as the teacher asked many questions about the students' models and/or asked for explanations for various important aspects related to the models, she used the visual mode more often than the students.

Finally, we view the low occurrence of the verbal model for both the teacher and students as a consequence of the criteria that we used to classify a representation as expressed in the verbal mode in this study. As previously mentioned, as our aim was exactly to analyse the role of non-verbal representations in explanatory and argumentative situations, we classified a mode of representation as verbal only when it was exclusively used—which was rare in the context we investigated.

The Representations and the Discursive Situations

As can be seen in Table 4, both the teacher and the students used the representations more often in explanatory situations. In part, this can be justified by considering that the modelling activities explicitly required the production of explanations (using the models produced by the students). They also favoured the occurrence of argumentative situations, but since the group was not used to participating in this practice, the teacher had a more significant role in these situations, questioning the students' models and their ideas expressed through the models. In this way, the fact that the students used the representations more frequently in explanatory situations than in argumentative ones could be related to explaining being a more common activity for them than arguing. As discussed by Duschl and Osborne (2002), argumentation is not common in the teaching and learning processes, while explanations are always present, even if they are not associated with dialogic discourse. Furthermore, in general, the argumentative situations were triggered by the teacher, while the students participated more by providing explanations than by seeking to argue. That is, while the students evolved with regard to argumentation during the modelling activities (as it was shown in Mendonça & Justi, 2013b), the teacher stood out more in these situations due to her role encouraging argumentation. This is not common, since it was shown by Driver et al. (2000) that, in general, teachers have difficulty dealing with activities that encourage discourse practices, such as the process for constructing and defending explanations.

With regard to the argumentative situations, we believe that the teacher used the representations more frequently than the students due to her role in the dialogues, which were to foster argumentation during the modelling, and to encourage discussion of the phenomena represented in the models. In this sense, many of the argumentative situations were triggered by the teacher when she questioned the groups about the characteristics of the models they had built. This occurred not only to help them perceive some inconsistency in the model (and therefore encourage a change to the model or the construction of another), but also to be certain that students understood the aspects that were represented (and accordingly, make sure they confirmed that their model was consistent with its aims). Both the role of the teacher and her more frequent reference to the representations in argumentative situations compared with the students are also consistent with the higher frequency with which she used representations in order to check student understanding (Table 3). This is because, although she did not present a model she was advocating, she motivated the students and participated in the argumentative situations, enabling the students to choose the better model by taking a critical position before it.

Considering the representational modes used by the individuals in each discursive situation (Table 4), we perceive that the concrete mode was mostly used by the teacher and by the students in argumentative and explanatory situations. We identified that, in the argumentative situations, the teacher used this mode much more than the students did, while in the explanatory situations, the students used this mode slightly more frequently than the teacher. This result is consistent with what we discussed previously in relation to the teacher's participation in argumentative situations, where she played the role of stimulator, criticising the students' concrete models and leading them to make changes necessary for a better model. On the other hand, although the students participated in these argumentative situations, they also sought from the teacher more explanations about conceptual aspects of the models. This could explain the fact that they used the concrete models more frequently in explanatory situations.

Conclusions

The analysis of the students' and teacher's multimodal discourse throughout the modelling activities allowed us to identify that both of them used representations with a similar frequency (103 and 92 times, respectively). Furthermore, the use of different representational modes, both by the students and the teacher, supported communication in the classroom, allowing for mutual understanding and the negotiation of meanings. This result was seen to be in line with other studies that highlight the fact that different resources for communication are common and necessary in science, especially in the case of chemistry (Adadan, 2013; Cheng & Gilbert, 2014; Gilbert, 2005; Kozma & Russell, 2005).

We stress the importance of our study with regard to students' use of representations, since they visualise and represent chemical processes and entities in a characteristic manner which is different, for example, from that of chemists. In this sense, our study showed relative diversity in the functions of the use of representations by the students and the teacher. We identified a total of seven different functions for the representations. Although our study took place in a specific context (teaching from modelling-based activities), it is possible that some of the functions of the categorised representations could be identified in other contexts, since they can be associated with the process of teaching science in general (e.g. the functions *to substitute specific scientific vocabulary* or *to explain a specific concept or aspect*).

We identified that, at times, students used different representational modes for the same function of the representation. Although our objective was not to investigate the individuals' capacity to move between different representational modes, we can highlight a specific aspect of our results related to this ability. The fact that the students were able to use and understand different representations (and in different representational modes) for the same entity or phenomenon, *but with the same function*, indicates one of their important abilities. This is because transition between different representational modes is one of the difficulties students have in understanding chemistry (Kozma, 2003; Kozma & Russell, 1997; Treagust & Chandrasegaran, 2009).

Specifically with respect to the representational modes used by the teacher, we noticed coherence with literature. Gilbert (2005) affirms that the concrete, visual, and symbolic modes are most common in the sciences, and these were the modes that the teacher used most effectively in discussions with the students.

With regard to the use of the representations by the students in the different discourses, they stood out overall in the explanatory situations compared to the argumentative situations. This is consistent with the fact that the function *to explain a specific concept or aspect* was most frequently used by the students. We mainly attribute this result to the fact that the students are more used to explanations than argumentation, since argumentation was not a common practice in that classroom—as is the case with classrooms in general (Duschl & Osborne, 2002). For students to be more at ease with this practice, it must become part of the culture of their classroom (Jiménez-Aleixandre, 2008), which was not the case with the class observed in this study.

As for the functions of the most recurrent representations in the teacher's discourse, we highlight *to check understanding*. Although other functions were also common with the teacher, this one, in particular, was directly related to the role she played throughout the discourse situations, mainly the argumentative ones. By questioning the students about aspects that were implicit in the models or which were not consistent with some conceptual aspects, the teacher encouraged the students to reflect on their models. In this way, we affirm that the teacher critically positioned herself during discussions and model presentations, guiding the students to reformulate the models (when there were inconsistencies) or to confirm them (when they were acceptable at that time).

Implications

The results of this study show some of the relationships between argumentative and explanatory discourses with respect to representations. In the introduction to a book on argumentation, Erduran and Jiménez-Aleixandre (2008) state that studies of multimodality in this type of discourse would be important. In this book, as in the overall majority of publications in the area, the authors discuss argumentation in relation to the verbal (oral or written) mode of communication. However, considering the various possibilities of multimodal discourse shown in our work, it is important that other studies involving representations and argumentative and explanatory discourses be conducted, so we can learn more about how representations contribute to the development of these discourses and about whether representations help in making decisions or resolving controversies (when we have competing explanations in the argument).

Another implication of our work is related to its contributions to discussions of the characteristics of argumentation and explanation. In studies about these practices in science, as well as in science teaching, differences, similarities, and confusion among these practices are presented. For example, Berland and Reiser (2008) propose that the process of constructing and defending explanations is permeated with argumentation, while Osborne and Patterson (2011) discuss whether the change of epistemological status from an *explanatory hypothesis* (among several) to an *explanation* that is consensual within a group is possible through the process of argumentation around distinct claims. In our study, we propose a characterisation of the functions of non-verbal representations in explanatory and argumentative situations, and we use them as categories to analyse a regular teaching situation. To construct our analysis instrument, we considered the main types of explanations present in the science classroom, as well as the most recurrent characteristics of argumentation, both supported by literature in the area (e.g. descriptions and causal relationships, in the case of explanations, and the use of justifications and evidence, in the case of arguments). Our conclusions indicate that non-verbal representations play important roles in the construction, use, and defence of explanations. Considering that the defence of explanations was the main context in which argumentative situations occurred in this study (the other was the discussion of codes of representation), the representations also contributed to the change of status of the students' explanations.

Another aspect that emerges from our work is the need to conduct studies on the use of representations in science education when the individuals using the representations are involved in another type of activity besides modelling-based ones. In our study, we worked exclusively with a series of modelling-based activities that directly encourage the creation and use of representations (mainly concrete ones). However, students' performance with respect to representations in other types of activities should be investigated, since this can result in proposing other possibilities for the teacher to discuss the students' representations and to encourage the development of skills related to the creation and the use of representations. Furthermore, the system we presented here to categorise the functions of representations can be used in contexts other than modelling, which would allow for a discussion of its degree of dependence on this context. In other words, the use of the system of categories in other contexts can allow us to identify which of the functions of the representations are specific, or more favoured, in modelling-based teaching contexts.

We also acknowledge that the system of categories for the functions of representations in argumentative and explanatory situations can be used in teacher training situations. This could foster a better understanding among teachers of (i) each of these situations; (ii) the role of representations in student learning; (iii) the importance of encouraging students to express their ideas in modes that are not necessarily verbal; and (iv) the role of representations in argumentative and explanatory practices. All of these aspects can contribute to more teachers working in a way that foster a more authentic science teaching, as was posited at the beginning of this paper.

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Notes

1. The evening classes mainly serve students who stopped studying for a time and/or work during the day. Consequently, the age range for these students differs from the typical age of students who attend that grade in the daytime (which is 14–15 years old).
2. Simplifications of scientific models that compose the school curricula (Gilbert et al., 2000).
3. For more details about classification of the elements of an argument, and their relationship with scientific knowledge, see Mendonça and Justi (2013b).

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