Analysis of students' diagrams explaining scientific phenomena

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While there has been much interest in the power of student generated multiple-representations to promote student reasoning and conceptual understanding, most studies of student explanations have been of written artefacts or only included diagrams as an adjunct to written explanations. This approach may be because teachers do not have an accessible framework with which to evaluate students' diagrams as being explanations. Adapting de Andrade et al.'s (2019) evaluation framework for written explanations, this study explored the benefits and limitations of a framework to evaluate students' explanatory diagrams. Seventeen Grade 5 and 6 students produced a series of explanatory diagrams over six chemistry lessons on particle theory. Their diagrams were coded and evaluated using the proposed diagram analysis framework. Some sample diagrams are included to illustrate how the framework assisted the evaluation of students' diagrams. The framework helped identify key features of students' diagrams and evaluate their explanatory powers consistently and effectively. This research also indicates that a series of stand-alone diagrams can effectively be used by teachers to assess how students communicate their understanding of causal explanations in terms of sub-microscopic entities of the underlying phenomena.

Researchers recognise the importance and the power of student-generated drawings in engaging students in learning and constructing scientific understanding (Ainsworth, Prain, & Tytler, 2011; Author, 2018; Hand & Choi, 2010; Tytler, Prain, Hubber, & Waldrip, 2013). However, when students are encouraged to represent their conceptual understanding through drawings, the majority of studies showed production of rather simple, single representations describing the phenomenon (Davidowitz, Chittleborough, & Murray, 2010; Ehrlén, 2009; Waldrip, Prain, & Carolan, 2010). Only a small number of studies have described students making a series of drawings or labelled diagrams to represent their explanations of scientific phenomena (Ainsworth et al., 2011; Akaygun & Jones, 2014; Author, 2020a). While the use of simple drawing exercises has been shown to yield benefits for students' construction of conceptual understanding, they have limitations in showing dynamic processes of scientific phenomena.

In her review of research on diagrams, Tippett (2016) noted that “learning from visual representations continues to be a common focus in explorations of diagram use in science” (p. 734), though a change in perspective did take place over a 15-year period of the review from learning *from* diagrams towards more learning *with* diagrams by students constructing their own representations. Nevertheless, classroom practice without the intervention of researchers would appear to focus on learning *from* diagrams despite the potential benefits for identifying and supporting students’ conceptual understanding when constructing their own drawings (Ainsworth et al., 2011). Another study to support this point that student-generated drawing activities are not widely adopted in science lessons was noted by Author (2014) who investigated science teachers’ instructional practice of using diagrams, having observed 120 lessons. The science teachers tended to encourage students to interpret diagrams provided to them rather than requiring students to create their own diagrams in class.

One major disincentive for adopting student-generated explanatory diagrams as a teaching strategy is the lack of a framework to evaluate the explanatory power of those diagrams (Chang et al., 2020; Cheng & Gilbert, 2009). The availability of such a framework could provide guidance to teachers about how to consistently evaluate student diagrams which may encourage more teachers to make use of diagrams as learning tools. While evaluation frameworks for pictorial explanations have been developed for specific topics, these may not be transferrable to other topics (Akaygun & Jones, 2014). Therefore, there is a need for more general guidance to teachers and researchers on how explanations through diagrams may be consistently assessed.

In our classroom-based research, we have witnessed that when immersed in drawing science diagrams and knowing what to include in science diagrams, students do rise to the challenge of representing their scientific causal explanations, including dynamic relationships and abstract concepts, when drawing a series of diagrams. By proposing an evaluation tool for explanatory science diagrams, this study shows how a series of student-generated diagrams can demonstrate students' scientific causal reasoning/explanations and what each level of diagrammatic explanation means/represents. This study aims to help distinguish the components of student-generated diagrams that constitute scientific causal explanations so that teachers know what to look for and how to cultivate the learning opportunities afforded by student-generated diagrams. In this study, we use the term, 'student-generated diagrams', rather than drawings or other similar terms, to reflect the nature of the task of drawing labelled scientific diagrams (Amare & Manning, 2007; Tippett, 2016). Students were aware that their diagrams should not only illustrate the phenomena they observed, but also explain why they happened.

A Framework for Evaluating Explanatory Diagrams

In the absence of generalised rubrics for evaluating diagrammatic explanations, we adapted a rubric designed by de Andrade, Freire, and Baptista (2019) to evaluate written explanations. The framework shows how persuasively students link macroscopic features with sub-microscopic features based on an underlying theoretical framework, such as the kinetic theory of matter, and can demonstrate a logical causal chain of relationships based on that framework.

Adaptation of the scheme of analysis

Using samples of students' written explanations in response to explanatory tasks, de Andrade et al. (2019) developed an evaluative framework for explanations of scientific phenomena. They noted that these explanations may be generally divided into non-causal explanations (non-explanations, macro-descriptions and mixed descriptions) and causal explanations (associative, simple scientific and complex scientific explanations). Each of these categories and their adaptation to diagrams are summarised in Table 1. The diagram categories are further elaborated below.

Insert Table 1 here

Non-explanations

A non-explanatory diagram is one that does not recognise the key observations of the phenomenon. For instance, if the task was to explain the difference between two scenarios, key observations would include the observable differences between those scenarios. In a non-explanation, while the equipment used may be represented, neither an explanation, key observations nor a description of a sequence of events relevant to the question is presented.

Descriptions

The diagrams describe key observations which are relevant to the question being posed without linking these to causal processes. In the example above, the key observations would be the observable differences between the two scenarios. Students' descriptions may be further subdivided into *macro-descriptions* and *mixed descriptions*. The former includes diagrams showing only macroscopic properties such as size, shape, temperature and state. Additionally, a mixed description includes some sub-microscopic characteristics (e.g., particles) but does not create causal relationships between macroscopic observations and these entities.

Associative Explanations

An associative explanation attempts to give a causal explanation of the observed phenomenon. However, a coherent, logical chain of events using the underlying model based on the interaction of sub-microscopic entities is not evident. The explanation may be given in terms of simple generalisations about relationships between properties (e.g., the explanation is based on differences in pressure without reference to particle collisions).

Simple Scientific Explanations

Establishing a causal explanation can be challenging because it requires students to make inferences from their understanding of interactions within the fundamental theoretical model (Braaten & Windschitl, 2011; Salmon, 1989). In order for a diagram to be deemed a simple scientific explanation in chemistry, the students must represent sub-microscopic entities such as particles and their interactions (e.g., speed, collisions, spacing, attractions, forces). Based on these entities and changes in their characteristics, a logical sequence of events is produced which is linked to the key observations. The reasoning focuses on a small number of characteristics (e.g., speed and collisions) and ignores other important characteristics (e.g., attractions). These descriptions of non-visible entities are represented as visible objects in student diagrams (Author, 1996).

Complex Scientific Explanation

Perkins and Grotzer (2005) noted that both students and teachers tend to produce *simple causal explanations* which follow one linear cause and effect relationship, particularly when explaining phenomena which occur as a result of probabilistic interactions. On the other hand, more complex explanations will theorize on the basis of a number of different cause and effect relationships based on models which represent reality and are evaluated on the basis of how comprehensive, plausible and coherent they are (Thagard, 2008). A *complex scientific explanation* or unification model (Friedman, 1974; Kitcher, 1989), builds on causal explanations by using theoretical models, such as the kinetic theory of matter (KTM), to develop explanations of apparently disconnected phenomena by invoking interactions described in these models to give a complex explanation of observations which requires sophisticated reasoning about a number of different interactions.

In order to provide a complex explanation, a series of why questions must be answered with causal descriptions which delve deeper into the observed phenomenon to find the links with an underlying theoretical model (Ohlsson, 2002). In this evaluation framework, those explanations that include more than one coherent chain of causal relationships between sub-microscopic entities/processes and macroscopic observations are classified as complex scientific explanations. In order to provide a complex explanation, non-visible entities such as molecules, their movement, fundamental forces and interactions (Salmon, 1978) must be invoked and a description of the different arrangement of these entities must be given. Further questions can be asked about these interactions until the answers to the 'why' questions do not include any more fundamental entities or relationships (Ogborn, Kress, Martins, & McGillicuddy, 1996). Figure 1 is a flow diagram showing a scheme of analysis to categorise diagrams according to the descriptions in this framework.

Insert Figure 1 here

The focus of this study is to demonstrate how students' explanatory diagrams can be analysed and categorised using the system of analysis adapted from de Andrade et al. (2019).

Methods

Research Design

This research was carried out as part of a larger study investigating the effect of producing science diagrams to enhance students' creativity. A constant comparative method of data analysis (Merriam & Tisdell, 2018) was used to compare similarities and differences between groups of diagrams to determine whether they could consistently be categorised in a similar way to which de Andrade et al. (2019) categorised written explanations.

Context and Participants

The context of this research was a science extension program designed to give greater academic challenges to students of Grades five and six (10-12 years of age). Based on a testing program for all grade four students by the Department of Education (2020) in the previous year, the students in this research study were identified as being gifted and eligible for academic extension. Seventeen students (16 males and 1 female) had chosen to study chemistry for one school term of 10 weeks and attended the program once a week for 2 hours. Pseudonyms are used for convenience when referring to different students. Each session was divided into two, with a short break in the middle. The experienced male primary school teacher had taught science in the extension program for the past five years and had volunteered to teach students with a focus on their explanatory diagrams. He received training in the teaching approach described below as well as support throughout lessons, including lesson plans, coaching in scientific concepts and questioning strategies prior to lessons, feedback on lessons and students' worksheets as well as how to give feedback to students on their diagrams.

The Lessons

A series of lessons were designed to build conceptual understanding of the kinetic theory of matter by challenging some commonly held alternative conceptions in this topic. Lesson topics, demonstrations and questions are described in Table 2. The format of the lessons was based on the Thinking Frames Approach (Author, 2020b; Newberry, Gilbert, & Cams Hill Science Consortium, 2011) and followed the general structure of: introduction of an experiment, predictions about the outcome, observation of the experiment and development of verbal explanations in small groups followed by a teacher-led class discussion. Students worked individually to answer the key question(s), which are presented in Table 2, through a series of explanatory diagrams (30 minutes). The students were asked to make their diagrams so that they would communicate an explanation of their observations to a third party. The teachers/researchers used Socratic questioning during the lesson to encourage students' deeper engagement with the underlying scientific model and elaboration of concepts in diagrams. Since this study covered a large number of topics, we focus on data from Lesson 2, which are presented in the Results section, where a more detailed explanation of that lesson is given.

Insert Table 2 here

Data collection

Data collection began after informed consent had been obtained from parents, students, teacher, the principals of each students' school and the coordinator of the extension program. Worksheets were collected, scanned and analysed. Video and audio recordings of small group discussions within each lesson were transcribed.

Analysis

Data were mined from student-generated artefacts as characteristics of each diagrammatic explanation were listed. Student diagrams were evaluated as stand-alone explanations of student understanding. Initially the descriptions of each category of written explanation given by de Andrade et al. (2019) were applied to each of the diagrams to tentatively categorise them. Further explication of each category was then made in relation to the components within the diagrams. As ambiguities or difficulties arose in categorising student diagrams, further elaboration was made of the categories in terms of diagram elements. Once the characterisations of each explanatory diagram category had been established and elaborated, the diagrams were re-evaluated to ensure that the framework and descriptions satisfactorily differentiated between diagrams and allowed consistent categorisation of diagrams. Peer reviews were made by each of the researchers to improve reliability of the framework and the evaluation of each diagram. Although the researchers did not ask students to explain the meaning of their diagrams, after evaluation of the diagrams using the adapted framework, transcripts of group discussions between students were checked to triangulate our interpretations of the diagrams.

Results and Discussion

Categorisation of Students' Diagrams Using the Framework

Diagrammatic representations produced by the 17 students over the six lessons were analysed using the adapted framework and presented in Figure 2.

Insert Figure 2 here

In order to illustrate the use of the framework to characterise students' diagrams, examples from Lesson 2 are presented with diagrams from each category. This lesson was chosen as the explanation levels of students' diagrams varied widely to allow a comparison of diagrams addressing the same question. The guiding questions (Table 2) for Lesson 2 were: 'Why does the temperature of the water increase and then stay at 100^{o}C? Why is the steam only at 100^{o}C? Where does the heat energy go to?'

Before being given the guiding question, students were asked to predict what the temperature of steam would be just above the boiling water in a pot with a lid on it. They discussed this in their small groups, then presented their explanations to the class. Students thought that the temperature of the steam would be much higher than the boiling water because they thought that it would have more energy. The temperature of the steam and water were then measured using digital thermometers. After observing that the temperature of both the steam and the water were approximately 100 ^{o}C, students discussed explanations for this observation in their small groups and presented their ideas to the class. The teacher used questioning to encourage students to consider ‘what happens to particles in water as they are heated?’, ‘what happens to particles when a liquid becomes a gas?’ and ‘what holds particles in a liquid together?’ Students were then given a worksheet (Figure 3) and asked to use diagrams to illustrate the explanations that they had constructed verbally. They were encouraged to use keys to explain symbols used and to make sure that their diagrams could act as a stand-alone explanation. Diagram features for each category are summarised in Table 3 to illustrate how the analysis framework may be used to differentiate students’ explanatory diagrams.

Insert Figure 3 here

Insert Table 3 here

Non-explanation. Alex’s diagram in Figure 4 is categorised as a non-explanation. While the diagram includes water particles and temperature change, it does not include the key observational features of the temperature of the water remaining constant at the boiling point and the temperature of the water and the steam produced being the same. The diagram indicates a number of alternative conceptions: particles in the boiling water are much further apart than particles in the water at room temperature; particles in water at different temperatures have the same amount of movement; ‘heat’ rather than steam rises off the surface of the water. There is no evidence of any causal relationships.

Insert Figure 4 here

Macro-description. No diagram was categorised as a macro-description in this or any other lesson. A macroscopic description of observations in Lesson 2 would have been a diagram of a heated pot containing boiling water and thermometers reading the same temperature for both water and steam. If the last diagram in Figure 4 had been presented alone it would have been a macroscopic description because it does not include any sub-microscopic particles or causal relationships.

Mixed-description. Bryan's diagram in Figure 5 describes the macroscopic observations relevant to the question: the temperature of the water increased as it was heated and the temperature of the steam and water at the boiling point were approximately the same. However, although Bryan used symbols to represent sub-microscopic water particles and show changes in their speed and collisions in the liquid water as the temperature increased, there is no causal explanation of how the energy is used at the boiling point. This is therefore a description of the observations relevant to the question rather than an explanation. Since reference was made to sub-microscopic particles, this diagram is deemed to be a mixed description.

Insert Figure 5 here

Associative Explanation. A change in energy or movement of the particles in the water between 60^{o}C and 100^{o}C is shown in Figure 6. The gas particles are slightly further apart than the particles in water and the faint lines between particles which, from the key, suggests energy was required to separate them and change phase. An alternative conception shows that the particles in the gaseous state have greater (average) speed than particles in the liquid even though they are the same temperature. Although Peter explained that energy is required to separate particles that are close together in a liquid, the focus is on the alternative conception that energy increases the speed of particles between the liquid and gas rather than on overcoming attractions between particles in a liquid. This diagram is therefore classified as an associative explanation. On the whole, the greatest difficulty was found in differentiating between diagrammatic explanations at the associative and simple scientific levels because there was some evidence of causal reasoning in the diagrams.

Insert Figure 6 here

Simple Scientific Explanation. In contrast to Peter, Ryan's response in Figure 7 focused on what was happening to the molecules in the water at the boiling point and described a chain of reasoning explaining how energy is being used to break apart what he calls bonds between water particles. Although the use of a key is limited, the molecules themselves are not being broken apart but the attractions between molecules are being overcome (see diagram labelled 'bonds'). Ryan used arrows to represent energy pulling the molecules apart and then described what happens when there is not enough energy to keep them apart, showing them reforming 'bonds' and becoming a liquid again. Like Peter (Figure 6), Ryan also held the alternative conception that the average speed of the molecules in the gaseous water is greater than the liquid water. However, the chain of reasoning for explaining why energy is needed to separate particles of a liquid to form a gas warrants the classification as a simple scientific explanation.

Insert Figure 7 here

Complex Scientific Explanation. Finally, Oliver's diagrams in Figure 8 provide a complex scientific explanation. He produced a logical sequence of diagrams which showed the effect of heat on temperature of the water and linked this with the speed of the particles. Oliver then showed that, when the temperature of the water had reached $100^{o}C$, the energy was being used to overcome the attractions between the particles of water and spread them further apart, thus changing phase and becoming a gas. Different numbers of wavy lines are used between particles to show that the attractions decrease as the particles get further apart. Oliver also recognised that the energy has been used to overcome these attractions rather than increase the average speed of the particles by using the same number of 'speed lines' on both the particles in the boiling liquid and the steam. In order to validate our interpretation of

Oliver's diagram, the audio/video recording of his discussion with peers whilst drawing was analysed which confirmed our understanding of his diagram. Figure 8 contains some quotations from him during the drawing process. This is a complex scientific explanation as it relates several different logical chains of reasoning (change in separation, change in attractions, and change in speed).

Insert Figure 8 here

Process of Categorizing Students' Diagrammatic Explanations Using the Framework

The most obvious benefit of using this framework for the teacher/researcher is that it facilitates consistent categorisation of students' explanatory diagrams in line with theoretical frameworks that describe important elements of a good scientific explanation. This framework addresses the need, identified by researchers (Chang et al., 2020; Cheng & Gilbert, 2009; Williamson, 2008), for a convenient tool to enable teachers to more extensively evaluate students' conceptual understanding through drawing diagrams.

Using the flow chart in Figure 1 to analyse a set of diagrams, the teacher/researcher needs to first identify the relevant observations that a student should refer to when answering the question. Those diagrams that do not represent these macroscopic observations fail to address the question and are categorised as non-explanations. If these observations are present the diagrams may be either categorised as a description or an explanation. Those diagrams that do not present causal relationships to explain the observation are deemed to be either macro-descriptions (without reference to sub-microscopic entities) or mixed descriptions (containing sub-microscopic entities).

If the diagrams show evidence of causal relationships to explain the observations on which the question is based, they may be further differentiated as associative, simple scientific or complex scientific explanations. As mentioned earlier, we found differentiation between the associative explanation and the simple scientific explanation categories challenging. While the simple scientific explanation contains a chain of reasoning, how complete do we expect this chain to be in order to deem the diagrams to be a scientific explanation rather than an associative explanation? In clarifying the difference between associative explanations and simple scientific explanations, we found it helpful to describe associative explanations as those based on the 'covering laws' model of Hempel and Oppenheim (1948). Covering laws do not invoke underlying sub-microscopic theoretical processes but explain the observations in terms of other observed regularities or algorithms, such as Boyle's law (Braaten & Windschitl, 2011). Use of a covering law to explain a phenomenon gives a limited explanation of cause and effect (Salmon, 1978) but does not encourage deeper engagement with the fundamental theoretical models of nature and the use of reasoning based upon these models (Driver, Leach, Millar, & Scott, 1996).

In the science classroom, explanations based on covering laws are frequently heard and accepted as sufficient by teachers (Braaten & Windschitl, 2011). In Lesson 2, the covering law would be that energy known as the 'Latent heat of vaporisation' is needed to change the state of liquid to a gas by separating its particles without changing its temperature. While this covering law is clearly based on an understanding of interactions between particles in each state, it is often used without reference to those interactions. By identifying this covering law, the student's explanation in Figure 6 is more easily categorised as simply representing this covering law without providing further explanation of what physical interactions are present between particles that necessitate energy being expended.

Consistent with observations of Perkins and Grotzer (2005), students who did present causal explanations tended to produce simple scientific explanations focusing on one chain of reasoning. As teacher/researchers we also found it difficult to determine which causal relationships to focus on in students' diagrams. We found it helpful to use the strategy of Ogborn et al. (1996) of continuing to ask 'why' questions until explanations based on theoretical interactions were exhausted. For instance, in Lesson 2 questions such as ‘what happens to the movement of the particles as the water is heated?’ ‘What is different about the arrangement of the particles in the liquid and the gas?’ ‘Why is energy needed to separate particles?’ ‘How is kinetic energy of the particles related to movement?’ ‘Why is the temperature the same in the gas and liquid at boiling point?’ ‘If the particles of gas have more energy than the particles in the liquid what form does this extra energy take?’ were asked.

After constructing these chains of reasoning, it was necessary to understand the reasoning presented by students and determine the levels of explanation that could be expected from these students based on their prior knowledge of the theoretical scientific model. By carefully examining students’ representations we were able to determine the interactions between sub-microscopic entities on which students most commonly focused. Through an iterative process of analysing and categorising students’ explanations, elements that described a simple scientific explanation and a complex scientific explanation were identified.

Benefits of Encouraging Students’ to Draw Diagrams with the Evaluation Framework

One observation that we made when applying the de Andrade et al. (2019) rubric was that the affordances of drawing diagrams led all students to consider the particle nature of matter and represent particles in some form in their diagrams (see Figure 2). This is evident from the absence of examples within the macro-description category in this study. Even those whose diagrams did not successfully link sub-microscopic processes with the observed phenomena generally recognised sub-microscopic processes such as particle movement and collisions (see Figure 2: mixed descriptions). An explanatory scientific diagram requires students to invoke more fundamental entities such as particles and their movement, fundamental forces and interactions. Whereas written explanations may refer to these fundamental entities and superficially refer to their interactions to provide a causal explanation (Nurrenbern & Pickering, 1987; Smith & Metz, 1996), a diagram that does not explicitly represent these entities will not be causal in nature. We would thus argue that production of explanatory diagrams affords a learning opportunity for students to seek more sub-microscopic causal explanations. Although the framework was adopted for a topic based on the KTM, further research is required to determine how successfully this framework may be used in other science topics.

Considerations and Limitations of using the Framework

This framework can be used by teachers to understand and categorise student diagrams. As illustrated in the results, the evaluations of the diagrams have been shown to enable a teacher to understand a lot of information about students' conceptual understanding of the topic without the need for interviews. The flow chart may appear complex, but the actual process of using it is not. Nevertheless, there are limitations in how the framework is used. Depending on how consistently a student identifies symbols used or how consistently they use symbols to represent their understanding, decisions about the explanation that the student is attempting to convey can be somewhat subjective. However, this is also true of written explanations where limitations in a student's written language skills may result in a teacher making subjective judgements about meaning. As with development of written skills, students require practice in developing the skills required to communicate effectively with diagrams.

Determining which diagram elements (see Table 3) are expected within each category may seem complex and time consuming. However, for a teacher to be able to systematically categorise the diagrams three aspects must be addressed. Firstly, based on the question, the key macroscopic observations of the phenomena should be identified. Secondly, teachers/researchers should be familiar with the covering law/s that explain the phenomenon.

Thirdly, teacher/researchers should develop chains of reasoning based on microscopic and/or sub-microscopic entities and processes in order to provide a complex explanation. Once these aspects have been determined, categorisation of the diagram becomes straight forward. Another limitation of this research is that it was carried out in a classroom of high achieving, highly motivated students. Further development of the framework and evaluation of its utility value to teachers in a variety of classroom environments and grade levels is needed to determine just how successfully this framework can be adopted.

Conclusion

This study demonstrates that a series of explanatory diagrams produced by students in response to observations can be evaluated to determine the level of explanatory power by means of the adapted analysis scheme of de Andrade et al. (2019). This analysis of students' diagrams allowing categorisation at different levels of explanation ranging from non-explanations to complex scientific explanations can provide a powerful alternative to written explanations for teachers assessing students' conceptual understanding of a science topic. From a research perspective, there has been substantial evidence of the benefits of student-generated diagrams for learning when students use diagrams to explain a scientific phenomenon (Tippett, 2016). Researchers have also documented students' diagrams as a measure of their understanding of science concepts based on sub-microscopic explanations of the underlying phenomenon (Tytler et al., 2013). While research using students' explanatory diagrams has generally involved students being required to elaborate what they wished to convey through their diagrams in interviews, in this study we have shown that students can convey complex explanations through diagrams without the need for the teacher to interview each student. These stand-alone explanatory diagrams can be used by students to communicate and develop their understanding of causal explanations in terms of sub-microscopic entities. However, missing from the literature has been a means for science teachers to analyse students' diagrams with a rubric to confidently evaluate students' explanatory diagrams. This study provides a convenient analysis tool for teachers wishing to implement a teaching strategy that involves student-generated diagram drawing activities. There are much needed studies to follow this one such as expanding this analytical framework so that teachers can give targeted feedback to students about how to develop their diagrammatic explanations.

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