Intentions and actions in molecular self-assembly: perspectives on students' language use

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Abstract

Learning to talk science is an important aspect of learning to do science. Intentions and purposes are part of the scientific language in explanations of unobservable objects and events. Teachers must therefore interpret whether learners' use of such language reflects a scientific understanding or inaccurate anthropomorphism and teleology. In the present study, a framework consisting of three 'stances' (Dennett, 1989) – intentional, design and physical – is presented as an analytical tool for analysing students' language use. The aim was to investigate how the framework can be differentiated and used for interpreting students' talk about a molecular process. Semi-structured group discussions and individual interviews about the process of molecular self-assembly were conducted with engineering biology/chemistry (n=15) and biology/chemistry teacher students (n=6). Transcripts were analysed qualitatively using content analysis. Students employed all three stances, and the analysis of utterances revealed subcategories for each stance. The analysis revealed that intentional language with respect to molecular movement and assumptions about design requirements may be potentially problematic areas. Students' exclusion of physical stance explanations may indicate literal anthropomorphic interpretations. The framework provides a powerful tool for analysing language use. It captures the use of anthropomorphic and teleological language regarding molecular processes while at the same time shedding light on the cognitive value of such statements. Implications for practice include providing teachers with a tool for scaffolding their use of metaphorical language and for supporting students' metacognitive development as scientific language users.

Keywords: Anthropomorphism; Language in classroom; Explanation; Qualitative research

Introduction

Language holds a pivotal role in science learning. Not only is speech and written text crucial forms of communication between humans, but learning to talk science is also in itself an important aspect of learning to do science (Lemke, 1990). This is emphasized by the importance placed on language in current international developments regarding standards for science education (e.g Lee, Quinn, & Valdés, 2013). Learning science thus includes pupils and students developing the communicative competences required to participate in scientific discourses. A potential problem in this regard is the use of language that describes non-sentient objects and processes in terms of agents that perform actions based on beliefs and goals. Indeed, from a very young age, humans tend to treat non-living objects as if they were goal-directed agents and explain their properties and behaviours based on perceived purposes (Johnson, Shimizu, & Ok, 2007; Kelemen, 1999). While literal interpretations of such utterances would give a scientifically inaccurate view of the described process, it nevertheless provides a very useful short-cut that avoids cumbersome physical details. In fact, such descriptions are an important and taken for granted aspect of scientists' communication in many fields, including biomolecular sciences (Rosenberg, 1986; Alberts, 1998), evolution (e.g. Ayala, 1970), microbiology (e.g. Shapiro, 2007) and immunology (e.g. Howes, 2000). This puts science educators in the difficult position of discerning whether pupils' and students' use of a language that invokes purposes and human characteristics indicates participation in a sophisticated scientific discourse or merely exposes a scientifically naive understanding of natural processes (Taber & Watts, 1996). Describing molecular processes in terms of beliefs, purposes and actions could be seen as a strategy of treating biochemical systems or their components as if they were conscious rational agents, which is clearly incorrect. However, given that humans constitute vastly complex biochemical systems, there is a point along increasing complexity after which this strategy might be the only way of interpreting behaviour. It seems that assessing learners' ways of expressing themselves about chemical and biological phenomena could benefit from a framework for categorizing language use with respect to different interpretive strategies. This study applies one such candidate framework on students' talk about a molecular process.

Intentional Systems

The framework used in this study originated in intentional systems theory (Dennett, 2009). It was introduced by Daniel Dennett as part of his exploration of the philosophical problem of consciousness, as a way of discerning the properties of systems that may hold beliefs. Briefly, he argues that whether or not a system can be claimed to be conscious depends on the perspective that outside observers need to hold to explain and predict the behaviour of the system. He defines an intentional system as a system that is complex enough and structured in such a way that an observer is required to treat the system as if it is rational and holds intentional states (e.g. beliefs, desires and perceptions) about its external surroundings. This strategy of prediction is called the intentional stance (Dennett, 1989), and it can be contrasted with explaining the system's behaviour through basic physical causation (adopting a physical stance) or by considering its construction (adopting a design stance).

It should be noted that the term intentional is used in the sense of "aboutness" (Dennett, 1983), that is, indicating that some state of the system is about something else (e.g.

“the cat believed that there was food behind the door”), rather than in the meaning “on purpose” (e.g. “the cat intentionally made scratch marks on the door”). In addition, claiming that something is an intentional system does not necessarily mean that it is a conscious being that is aware of its intentional states.

Together, the three stances described above captures important ways of approaching interpretation, explanation and prediction of the behaviour of biomolecular systems ranging from atoms to organisms. Therefore, it seems like a good basis from which to develop a framework for assessing learners’ language use in chemistry and biology education. Although the conceptual framework from intentional systems theory has not been applied previously in science education research, clues to its potential utility can be found in literature on the tendency among pupils and students to include teleological and anthropomorphic expressions in their explanations in biology (e.g. Abrams, Southerland, & Cummins, 2001) and chemistry (e.g. Taber & Watts, 2000). In the following, a brief overview of findings related to potential problems and possibilities associated with learners’ use of anthropomorphic and teleological language is given, and possible links to the three stances described above are made.

Anthropomorphisms, Teleology and Intentional Language in Science Education

Anthropomorphism entails giving human characteristics to non-human objects or phenomena, while teleology is used when an explanation of, for example, an event or the existence of a structure includes a purpose or a goal. Teleological explanations may include anthropomorphism if the purpose or goal is ascribed to a conscious agent. By the same token, explanations that include anthropomorphisms are not always teleological, because the human characteristics could include other aspects than purposes and goals (Talanquer, 2007).

Problems related to learners’ anthropomorphic understandings of cells is frequently raised in the literature (e.g. Dreyfus & Jungwirth, 1989; Flores, Tovar, & Gallegos, 2003;

Byrne, Grace, & Hanley, 2009). For example, Flores et al. (2003) observed that anthropomorphic reasoning with respect to cells among high school students may be accompanied by inappropriate analogies between cells and macroscopic organisms, leading to incorrect conceptions of cells and cellular processes. For example, some students claimed that a cell makes decisions based on what it requires, and that cellular reproduction occurs through mating between two cells. The first of these examples might be seen as a case of adopting the intentional stance (by treating cells as rational decision makers), while the other might indicate adoption of the design stance (by assuming that humans and cells are designed in the same way). Although both may be characterized as anthropomorphic, there are clear differences that may be untangled by applying the three stances.

Learners' potential difficulties has also been linked to teleological or anthropomorphic reasoning in chemistry, sometimes included in explanations from teachers and textbooks (Orgill & Bodner, 2006; Talanquer, 2007; Treagust, Chittleborough, & Mamiala, 2003). For example, Tytler, Prain, and Peterson (2007) described how children explained the spread of a scent through air in terms of directed molecular movements, as if the molecules could move purposefully on their own. Treagust et al. (2003) discuss the risk that anthropomorphic explanations gives rise to misunderstandings when students are unfamiliar with the anthropomorphic metaphors, for example the claim that some groups of the periodic table exhibit "schizophrenic chemical behavior". These two examples indicate that anthropomorphic expressions come in different forms also in chemistry, which might be separated using the three stances. In this case, the first example could be interpreted as adoption of the intentional stance, while the latter might actually be a case of adopting the physical stance, although expressed using a metaphor. Chemistry textbooks have been found to frequently contain teleological formulations, for example in describing the behavior of a chemical system as guided by the goal of maximizing or minimizing a property such as stability (Talanquer, 2007). Such explanations could be interpreted as either adopting the design stance or the intentional stance, depending on whether the purpose is expressed as an intentional state or not.

Several authors argue that although teleological and anthropomorphic expressions could hinder learning, they may also be beneficial to students' understanding. In this regard, Byrne et al. (2009) view anthropomorphisms as a potential tool to enable further learning among primary and secondary pupils in the context of microbiology. According to Talanquer (2007), teleology in textbooks may be seen as didactical transposition and has heuristic pedagogical value in that it provides "an explanatory reason for the occurrence of chemical processes" that can potentially simplify complex formulations. Along similar lines, Kattmann (2008) argue that anthropomorphism is an unavoidable consequence of the embodied basis for pre-scientific conceptions, and that education should make use of the powerful learning opportunities that it provides. Taber and Watts (1996) distinguish between "strong" and "weak" anthropomorphism, where the former denotes students' apparently literal interpretation of anthropomorphic statements and the latter refers to a metaphorical interpretation.

Agency and Goals in Biological Scientific Discourse

Despite the problematic mapping between teleological explanations and anthropomorphic descriptions, on the one hand, and physically-based causal mechanisms in biology and chemistry on the other hand, it is nevertheless the case that such expressions are used by experienced scientific practitioners, which has consequences for education. In evolutionary science, a bird that behaves as if a wing was broken may be described as using a deceptive strategy for luring a predator away from the nest. Although it may appear intuitively appropriate, the seemingly anthropomorphic and teleological term “strategy” is used in a redefined manner that indicates that the behaviour serves a purpose but does not mean that the individual bird is consciously aware of this purpose. Adopting the intentional stance to evolutionary processes in this way has been called the problem of “free-floating rationales” by Daniel Dennett (1983).

Similarly, teleology, understood as the position that the outcome of a process is the causal reason for the process to occur, is scientifically incorrect because future events do not cause natural processes to occur. However, this is not necessarily the way teleological explanations are actually used in science. For example, Ayala (1970) argues that natural selection is teleological in the sense that it leads to a maximization of reproductive success, but it does not actively select for specific adaptations in organisms.

The molecular sciences are also associated with a language that frequently include anthropomorphic language. This is clear from the very concepts used, such as “molecular recognition” and “targeted drug delivery”. Rosenberg (1986) claims that such descriptions of molecules in scientific discourse actually use intentional language in an implicitly redefined way, just like the explicit redefinition of terms such as “strategy” in evolution. This way, scientists can conveniently describe the function of a system by substituting an intentional description for a detailed physical description of the system that would be much longer.

Self-Assembly and Intentionality

As described earlier, intentional states are always about something, and intentional expressions in biology are in this sense not merely convenient short cuts - they also communicate the important “aboutness” of structures and processes which are often necessary to understand to fully explain biological phenomena (Howes, 2000). For instance, biomolecular self-assembly is the fundamental process through which subunits spontaneously associate into well-defined molecular complexes. Thus, order comes about from disorder at the molecular level in systems of structurally complementary molecules that interact through random collisions (e.g. Höst, Larsson, Olson, & Tibell, 2013). Here, the physical and chemical properties of the interacting molecular surfaces match each other, which means that the macromolecules can be described as expressions of genetically encoded information about the structure of their binding partners. This implies that while expressing these binding events in terms of intentional states such as “recognition” is obviously not formally correct, it nevertheless communicates that there are underlying reasons for why the surfaces are in fact complementary to each other (i.e. they have been selected by natural selection based on their capacity to bind to form a complex with each other). Laszlo expressed this observation succinctly by noting that “the self-assembly metaphor harbors the notion of a molecule that, once it has been designed for a given function, will carry it out on its own” (Laszlo, 2004). Hence, self-assembly may be one example of a process that is potentially inviting to descriptions that include some kind of agency.

Aim and Research Questions

Clearly, the proper language use in the biological and molecular sciences is a complex area, with many coexisting discourses used by scientists, teachers and textbook authors. The existence of redefined meanings of expressions that would otherwise be considered non-scientific (Rosenberg, 1986; Dennett, 1983) indicates that a complete avoidance among learners of anthropomorphic and teleological descriptions is neither realistic nor desirable. Rather, what is needed is a framework for interpreting learners’ expressions that allows for a variety of perspectives. Therefore, the aim of this study is to apply and elaborate the three stances of intentional systems theory (Dennett, 1989) to analyse learners’ language use with respect to scientific phenomena. Given this aim, the study was guided by the following research question:

- How can a framework consisting of intentional, design and physical stances be differentiated and used for interpreting students' talk about a molecular process?

Methods

Study Design

For the present study, the important molecular process of self-assembly is used as the scientific context for investigating language use. The study was conducted as part of a project which investigated students' learning about molecular self-assembly. Earlier results from the project has concerned students' learning outcome from a group-based intervention using a tangible model and an image from a textbook (Höst et al., 2013) and the significance of a tangible model with respect to the counter-intuitive nature of self-assembly (Larsson & Tibell, 2015). Data collected in the project included situations where students had the opportunity to express themselves verbally about the molecular process, in the form of individual interviews and group discussions. In the present study, the data were used to gain knowledge about students' language use in science education by analysing the verbal data with respect to the described framework of the three stances from intentional systems theory (Dennett, 1989). The sampling targeted students in their early university studies, whom can be expected to have a fairly well-developed understanding of the molecular scientific context while still being novices with respect to the scientific community

Sample and Data Collection

The study was conducted in conjunction with an introductory biochemistry course at a Swedish university. The first author was involved with teaching at the department, although not with the participating students. The participants were Swedish university students studying for degrees in engineering biology and chemical engineering (n=15, 11 female and 4 male), or to become chemistry or biology teachers (n=6, 3 female and 3 male). Ages ranged between 20 to 30 years. Data were collected in the form of semi-structured individual interviews and group discussions in the context of biomolecular self-assembly. All students that were enrolled in the course were invited to participate in the study. Participation was entirely voluntary but all students chose to participate and provided their written consent after being informed about the study.

Interviews

Semi-structured interviews (Kvale 2009) were conducted with six student teachers. First, the students were given a paper with text and images describing background information about haemoglobin (see supplementary material Table S1). The interviewer commenced the interview by asking the student to explain how the haemoglobin subunits and the heme groups come together to form complete haemoglobins in the cell from free molecules. Following this initial probe, the interview proceeded with follow-up questions that the interviewer formulated during the interview depending on the student's responses. The aim with the follow-up questions were to encourage the students to respond as fully as possible to the initial probe question, either by redirecting them if they strayed from the topic, or by asking them to expand on their explanation. During the interview, care was taken to formulate the interview questions to avoid introducing any biases towards anthropomorphic interpretations of the process. The interviews lasted between 15 and 30 minutes and were audio recorded and transcribed verbatim.

Individual interview data were only collected from the teacher students. The reason for this is that the data were collected in the context of studies that investigated conceptual understanding of the self-assembly process (Höst et al., 2013; Larsson & Tibell, 2015) rather than students’ language use. Given that the interviews and a written test yielded the same information about the status of the students’ conceptual knowledge, namely that they knew little about self-assembly, interviewing the other students was not expected to contribute enough information about students’ understanding to be warranted in the original data collection context.

Group Discussions

Group discussions were conducted as part of an activity related to biomolecular self-assembly during a biochemistry course. During the sessions, the students were encouraged to discuss various aspects of the self-assembly of a virus capsid using an interactive tangible virus model (Höst et al., 2013). A researcher took the role of discussion facilitator based on a semi-structured group discussion guide (see supplementary material Table S2). The exercise contained a set of tasks, each of which instructed the students to manipulate the physical model in a specific way. Following a task initiation question (e.g. “How is assembly achieved during virus production in vivo?”), students used the virus model as a focus instrument in discussing the question. The facilitator posed scripted follow-up questions (e.g. “Do the subunits always assemble in the same way?”), but did not otherwise participate in the discussions.

A total of four group discussions were conducted, with group sizes that ranged between 4 and 6 students. The students that were interviewed individually were in Group 4, except for S6 who did not participate in a group discussion. Each group discussion took between 30 and 45 minutes. The sessions were video and audio recorded, and the recordings were transcribed verbatim.

Data Analysis

The transcribed interviews and group discussions were analysed qualitatively using a combined deductive and inductive (cf. Hsieh & Shannon, 2005) approach to categorise and characterise ways in which the students talked about molecular events in the context of biomolecular self-assembly. The analysis followed a qualitative content analysis trajectory (e.g. Graneheim & Lundman, 2004; Elo & Kyngäs, 2008), using the combined text corpus composed of the transcripts from individual interviews and group discussions as the unit of analysis. The transcripts were read several times to get an overall feeling for the data, followed by identification of semantic units (Baxter, 1991) that expressed a molecular content. This involved discerning parts or whole statements made by single participants in which they described properties, events, tendencies and other aspects related to the area of molecules and molecular processes. The identified statements were used as meaning units that were subsequently categorised (Graneheim & Lundman, 2004).

In pursuing the research aim, the analysis was based on an intentional systems perspective that characterises three different stances (physical, design, and intentional) in describing the behaviour of a system (Dennett, 1989). Therefore, a first phase of the content analysis consisted of deductively assigning each condensed meaning unit to one of the three stances. The second phase was to inductively categorize the utterances within each stance into subcategories. Although the analysis was iterative, resulting in partly parallel deductive and inductive categorisation processes, each will be described separately in more detail in the following.

In preparation for the categorisation, the identified meaning units were condensed in an attempt to capture the key features of students' assignment of causal relationships and potential agency among molecular entities. For each meaning unit, assignment of one of the three stances was then based on an assessment of the nature of any causal connections (cf. Russ, Scherr, Hammer, & Mikeska, 2008) included in the meaning unit and whether functional reasoning was employed. The following criteria were used to guide the assignment of meaning units to the three stances.

Meaning units were assigned to the *intentional stance category* when students seemed to interpret the self-assembly process by treating something in the process (e.g. a subunit, RNA, the complete virus, or other molecules) as if it were a rational agent that has intentional states, such as beliefs and desires, which it considers in deciding its actions. Assignment of meaning units to the *design stance category* was based on students' seeming to assume that something in the self-assembly process was designed to perform a certain function and that it can be expected to work as designed. Assignment of meaning units to the *physical stance category* was based on students appearing to treat the self-assembly process as if it were governed by physical principles that explain the behaviour based on the physical constitution of the components involved in the process.

The possibility that meaning units did not fit any of the three stances was also considered during analysis. The analysis resulted in a categorisation of meaning units, where each analysed utterance was uniquely assigned to only one stance.

The meaning units within each stance were analysed inductively to develop subcategories providing a more detailed view of the different ways that students' use of each stance were revealed in their utterances. Here, the meaning units within each categorised stance were reviewed to search for salient features that defined their membership in the category in an open coding process (Elo & Kyngäs, 2008). Thus, the inductive analysis constituted a process of specifying what features in each meaning unit that actually supported the choice to categorise it to one of the three stances. Given that this process involved a more detailed analysis of the meaning unit content, it could in some cases result in the recategorisation of a meaning unit to another stance. It is in this sense that the dual deductive/inductive analyses were done iteratively and in parallel.

Although the two authors were engaged in continuous discussions throughout the analysis procedure, the initial coding and development of categories were conducted by the first author. This author is a science education researcher with a research background in molecular biotechnology, and is therefore well aquainted with the language use of learners as well as of scientific experts. Apart from the dialogue between the authors, credibility of the analysis procedure was pursued through the following approaches. Peer examination (Merriam, 2009) was performed throughout the analysis procedure, during which tentative findings were discussed at work-in-progress seminars with research colleagues. Among the attendants were collaborators in the wider project about students' learning of self-assembly. Since they had participated in the data collection and analyzed parts of the data in other studies (e.g. Larsson & Tibell, 2015), and therefore had a deep familiarity with the data corpus, they were able to give valuable feedback on the developed codes and categories in the present study. Reliability was further supported by the observation that the collected data appeared to be saturated (Merriam, 2009) in the sense that all resulting categories occurred in multiple data sets.

Results

Qualitative content analysis of the six individual interviews and four group discussions isolated a total of approximately 250 meaning units, where students expressed themselves regarding events at the molecular level. Of these, 64 were categorised as representing an intentional stance, while 56 and 121 were assigned to the design stance and physical stance categories, respectively. Utterances in each of the stances were further categorised into subcategories in an attempt to specify the nature of the features through which the respective stance emerged in the meaning units. This analysis revealed four subcategories for the intentional stance, three for the design stance and three for the physical stance. In the following, the subcategories will be described in more detail for each of the stances.

Intentional Stance

Students' used the intentional stance in four distinct ways. These differ in the type of intentional state that was invoked in the utterances, and thus represent the observed variation in "aboutness" in the implied relation between rational agents and their surrounding context.

Emotion: The subcategory Emotion includes students' utterances that refer to emotional states of molecular entities. In the current study, the term emotion is used in a way that include variations and combinations of typical "primary emotions" (e.g. Turner, 2009) such as anger, fear, sadness, and happiness. In the observed examples, it was used to contrast the current state with the predicted effect of an alternative state. For example, one student predicted the effect on a virus from the increased temperature associated with fever by expressing that:

Q1: "...then the virus will not be comfortable..." (Group 2, group discussion)

Similarly, a student motivated that subunits associate with each other based on the emotional effect that this has:

Q2: "In some way they have to aproach each other, otherwise it will not be any fun." (S4, Group 4, group discussion)

Knowledge: In the Knowledge subcategory, students explain molecular events by appealing to knowledge among the molecular entities. Among the utterances where explicit statements that objects have the relevant knowledge that is required for them to participate in the process:

Q3: "In some way the pieces know where they should be" (S1, individual interview)

Other utterances where more subtle, for example expressing that the subunits are endowed with the knowledge required to evaluate and compare two situations, and use it as a basis for decision-making with respect to the goal of the process:

Q4: "…when they encounter each other they need to somehow realize that this is a better condition than it is to be each on its own" (S4, Group 4, group discussion)

Perception: The subcategory Perception includes descriptions of molecules' sensory experiences or capacities. This subcategory includes statements where molecules are described as having direct sensations of their surrounding or as gaining information about their surroundings in a way that implies some form of sensory modality. For example, one student argued that attractive forces between subunits are important by expressing that:

Q5: "They will also feel the attraction from each other." (S5, Group 4, group discussion)

A potential issue in the interpretation of this quote is the possibility that "the attraction" may be intended as a metaphor in the interpersonal sense of a mutual romantic or sexual interest rather than the scientific sense of a physical force. Such an interpretation would place the quote in the Emotion subcategory. However, it seems most likely that the student use the term in the scientific sense, given the frequent use of attraction and repulsion in biochemistry in general, and the present study context in particular (e.g. see quote Q20 below).

Another type of competence related to perception that students associated with the molecular process was the ability to conduct a search to find a specific object or target:

Q6: "I think that they move in such a way that they will find their corresponding [binding partner]" (S5, individual interview)

Will: The Will subcategory contains utterances in which students assign preferences or motivations for action. In the following example, a student expresses the effect of an increased concentration of other macromolecules in the solution:

Q7: "...if there is too much of something in the solution, they will not want to sit by each other..." (Group 1, group discussion)

Some of the utterances in the Will subcategory only invoked a will implicitly, for example by describing the level of difficulty for subunits to perform certain actions:

Q8: "… it should perhaps still be more difficult for them [the subunits] to bind" (Group 2, group discussion)

While not explicitly referring to a molecular will, such formulations only make sense under the assumption that the molecules have an intention to bind and an ability to try (Taber & Watts, 2000). Similarly, other utterances conveyed action performed by agents to achieve specified goals. For example, the following quote describes the use of enzymes as a solution to the problem of achieving a high rate of change, which implies the presence of a will:

Q9: "It has to exploit some kind of enzyme so that it could be relatively rapid" (Group 3, group discussion)

A small fraction (2 and 4 statements in Group 1 and 4, respectively) of the utterances explicitly rejected an intentional stance as a reasonable approach for talking about molecules by pointing out perceived limitations in intentional interpretations (e.g. "...it is not like it has a mind of its own"). These statements are not included among the reported intentional stance statements in Table 1.

Design Stance

The design stance category contains three different subcategories. They differ in what aspects that are emphasized in relation to the purpose of the system.

Structural fit: The Structural fit subcategory contains utterances wherein students describe or refer to the relative arrangement of components. Among these were expressions that emphasize that the system is composed of parts that fit together in a specific way, sometimes accompanied by an analogy:

Q10: “...it [the virus capsid] is like a kind of jigsaw puzzle, it [a subunit] fits in just the place where it should be…” (S1, individual interview)

Other examples implicitly related the structural fit between parts to an overall purpose of the structure formation by evaluting relative positions of the parts in terms of whether they were positioned correctly or incorrectly:

Q11: “the correct ones sit more firmly than the ones that sit incorrectly” (Group 2, group discussion)

Function: The Function subcategory contains statements that refer to functional aspects of the process of self-assembly. Among these were explicit references to functions that the students expected participating parts in the process to perform. For example, in response to the possibility that subunits bind to each other in the wrong way, one student expressed a prediction that the process must involve some kind of (unspecified) subprocess that can be interpreted as having the function of correcting errors:

Q12: “It will correct itself, hopefully.” (Group 2, group discussion)

Students also expressed expectations regarding which objects they thought were needed based on functional considerations:

Q13: “there has to be different enzymes and such that … shape them [the subunits] so that they can be put together like a jig-saw puzzle” (S6, individual interview)

Purpose: The Purpose subcategory contains students' utterances wherein they explicitly stated the perceived purpose of the process. In some cases this referred to the end result of the specific molecular process:

Q14: "In this particular case it is supposed to become a ball..." (S2, Group 4, group discussion)

In another example, a student relates the formation of virus capsids with its ultimate purpose for viruses:

Q15: "The purpose is maybe that they [virus capsids] shall exist so that they can send DNA over here." (S3, Group 4, group discussion)

Physical Stance

The physical stance category contains three subcategories. Each of these contain utterances in which students refer to physical phenomena of different types. It should be noted that there is an inherent ambiguity in interpretating students' molecular talk that arise when students' express molecular events in terms that make them sound like actions (e.g. X "binds to" Y). Such utterances have been assigned to the Physical stance unless they also contain some other aspect that is associated with the Intentional stance (e.g. Q8 above).

Movement: The Movement subcategory contains students' utterances concerning changes in position. In some cases, the description specifies a type of movement that implies contact with other objects, for example by using a verb that by definition involves a smooth contact with a surface:

Q16: "These small pieces will slide around somehow" (S3, Group 4, group discussion)

Other examples include utterances about the location where objects end up. In the following example, a student entertains the possibility that a subunit may arrive inside a forming virus capsid:

Q17: “…that something ends up inside.” (Group 2, group discussion)

Interaction: The Interaction subcategory contains statements in which the molecular events are described in terms of forces between objects. For example, the following statement relates binding between subunits to stability of a complex.

Q18: “But once they have bound they may perhaps be more stable” (Group 2, group discussion)

Other examples refer to the types of encounter that may occur between molecules:

Q19: “…they collide … and they come in close enough to bind together” (Group 3, group discussion)

Q20: “… well, it is probably repulsion and … attraction between different molecules” (S4, individual interview)

Process: The Process subcategory contains utterances wherein students focus their descriptions on the unfolding of chemical or biological events. For example, in the following quote, a student refers to the random aspect of the self-assembly process:

Q21: “they could … be put together relatively randomly” (S3, Group 4, group discussion)

In the following example, a student predicts the effect on the self-assembly process from a change in environmental conditions:

Q22: “If it becomes too hot it will be too much [collisions], and then they will break” (Group 2, group discussion)

Patterns in Students’ Use of the Three Stances

Students’ use of the three stances exhibit tentative patterns in the data. Table 1 shows that each group discussion included all three stances, but the physical stance was observed more frequently than the other two stances in the three groups of biochemistry students (group

1 - 3). Indeed, approximately half of the identified utterances in these three group discussions were categorised as the physical stance, with different distributions of design and intentional stance-associated utterances. The student teacher group (group 4) displayed a different pattern compared to the other groups, with an even balance between the three stances.

Table 1. Distribution of meaning units among the main categories in students' group discussions about biomolecular self-assembly

Group	Physical stance	Design stance	Intentional stance
Group 1 (n=4) 47	28 (60%)	6 (13%)	13 (28%)
Group 2 (n=5)	26 (66%)	8 (21%)	5 (13%)
Group 3 (n=6)	13 (57%)	4 (17%)	6 (26%)
Group 4 (n=5) 64	23 (36%)	22 (34%)	19 (30%)

Examples of individual-level language usage were revealed through the individual student interviews, see Table 2. Here, all of the interviewed students included the physical stance in their explanations. Two students did not include any statements related to the intentional stance, while one did not include any statements related to the design stance.

Table 2. Distribution of meaning units among the main categories in six student teachers' individual semi-structured interviews about biomolecular self-assembly

Student	Physical stance	Design stance	Intentional stance
S1	3	5	2

S2	5	0	2
S3	4	3	2
S4	5	3	0
S5	3	2	16
S6	12	4	0

One of the interviewed students (S5, Table 2) expressed a view of how molecules interact that was almost entirely based on the intentional stance. This students' explanation attached rather advanced cognitive abilities to the interacting molecules. They were described in terms of a general goal-directed behaviour, a description that was further elaborated by suggesting that subunits know where their correct place is:

Q23: ”well, they have a built-in map of how it is supposed to look” (S5, individual interview)

Another student (S1) used partly anthropomorphic explanations for how the subunits come together, although the student also claimed a lack of knowledge about how the pieces come together. Two students (S3 and S6) provided explanations for self-assembly that invokes unspecified enzyme activity (e.g. Q13).

Although students were not able to provide accurate accounts of self-assembly during the interviews, it was nevertheless clear that the students understood what the focus of the interview was, as exemplified by the following student after proposing a potential explanation for the configuration of subunits in the formed complex:

Q24: ”But that does not explain why they come against each other to begin with.” (S3, individual interview)

Discussion

Learning to talk science is a crucial goal of science education (Lemke, 1990). This includes developing an appropriate understanding and use of ambiguous language that may be "non-scientific" but still an important part of the way scientists express themselves (e.g. Rosenberg, 1986; Rundgren, Hirsch, Rundgren, & Tibell, 2012). In the following, the different ways in which students' use the stances will first be discussed and related to potential problems arising from anthropomorphic and teleological reasoning, followed by reflections on the study's implications for practice and methodological limitations.

Students' use of the intentional stance endows objects at the molecular level with abilities that are typically associated with humans. In this sense, the subcategories within this stance may be viewed as anthropomorphic. Assignment of emotion is a very clear case of this. In the observed examples, emotion appears to serve as a value-indicator of the state of the system. For example, utterance Q1 may be interpreted to mean that an increased temperature is negative for a virus' continued existence and reproduction. In this regard, previous research has shown that students often use anthropomorphisms as a short hand for a detailed physical description (Zohar & Ginossar, 1998).

While it is difficult to distinguish between students' use of 'weak' anthropomorphisms of metaphorical or redefined intentional language and 'strong' anthropomorphisms of literally interpreted intentional statements (Taber & Watts, 1996), the literal mapping of predictions from an intentional stance onto the molecular world may be particularly misleading for molecular movements. Kattman (2008) has suggested that learners' tendencies to anthropomorphize unobservable processes and objects using intentional terms may stem from a lack of direct bodily experiences on which to base their conceptions of such phenomena. As a consequence of the bodily context of students' use of the intentional stance, stating that a molecule knows where it should be (Q3, Knowledge) or has a capacity for searching (Q6, Perception) may, if taken literally, indicate expectations that molecules will move only in the appropriate directions. Thus, conceptions of molecular movement based on intentional stance interpretations could result in inappropriate analogies between macroscopic events and activities, and the essentially random movement patterns of submicroscopic phenomena (cf. Flores et al., 2003).

A further complication is that students tend to believe that random processes are very inefficient, while biological systems are efficient (Garvin-Doxas & Klymkowsky, 2008). Students may therefore expect “drivers” that are responsible for the efficiency of the process (e.g. Q9). By the same token, since the emergent macroscopic outcome (i.e. the formation of viruses and further infection) may be believed to be well-ordered and efficient, such properties could be projected onto the individual submicroscopic molecular encounters, a perspective that has been called ‘submergent’ by Rappoport and Ashkenazi (2008).

In using the design stance, learners talk about molecular properties and processes in terms of their relation to a purpose. Student quotes in the Purpose subcategory could therefore be viewed as teleological in that they focus on the purpose of the process as important for the progress of the process. However, learners’ use of a teleological language does not necessarily imply teleological reasoning (Zohar & Ginossar, 1998). Indeed, in the cases found in this study, the expressed purposes did not seem to play causative roles in the process as in classical teleology (e.g. Ayala, 1970). Rather, they could be viewed as reminders about the context of the problem-solving activity (Q14) or interpretations of where the process fits in a wider biological context (Q15).

Treating a molecular process as if it were designed includes structure-function analysis, which is a very important aspect of the molecular sciences (e.g. Alberts, 1998). This is clearly indicated by the design stance subcategories Structural fit and Function. While essential for molecular reasoning, the implicit assumption that a system is designed to function well may also contribute to the view that random molecular encounters are insufficient for a system's proper functioning. For example, Q13 suggests that enzymes must be involved for the continuation of the process (see also Q9). In addition, adopting a design stance may be confused with the assumption that there must exist a designer, as exemplified by proponents of the Intelligent Design movement in mapping the existence of a designer for any man-made machine onto their argument that evolution of complex molecular assemblages is impossible (e.g. Höst & Bohlin, 2015).

The presented framework include students' interpretation of molecular processes from a physical stance. Here, the Movement and Interaction subcategories are related to the fundamental dynamics and forces among molecules, while the Process subcategory captures descriptions of ongoing molecular activites in relation to the molecular process. Interestingly, the analysis did not reveal any subcategory of learners' descriptions of molecular structures from a purely physical stance.

The results indicate that while students, at individual and group levels, differed in their preferences for using the three stances, most used all three to some extent. The finding that there may be a potential difference between the teacher student group and the engineering students in the distribution of the stances indicate that more student groups should be investigated. Among the participants, there was one student that appeared to use the intentional stance as the main cognitive tool for explaining the process of biomolecular self-assembly. The lack of any physically-based explanations strengthened the impression that this student used the intentional language non-metaphorically. Students' consistent use over time of mainly the intentional stance could therefore be an indication of a 'strong' anthropomorphic understanding (Taber & Watts, 1996).

Implications for practice from the preceding discussion indicates that teachers could use the presented framework to aid them in identifying potentially problematic usages of intentional and design stances. In particular, intentional stance interpretations of movement and design stance predictions about requirements based on unfounded assumptions could be given extra attention. In addition, a heavy emphasis over time on intentional expressions from students in the classroom may be a sign of a lacking ability to translate between concrete and metaphorical descriptions of molecular processes. Here, teachers may use the framework with respect to students' science talk to distinguish between 'implicitly redefined' (Rosenberg, 1986) or metaphorical (Taber & Watts, 1996) usage of intentional language, and a 'strong' anthropomorphic understanding of nature among students. Teachers could also use the framework as a background for scaffolding materials (Kawalkar & Vijapurkar 2013). For example, students' metacognitive awareness (González Galli, & Meinardi, 2011) regarding potential pitfalls inherent in literal interpretations of scientific discourse could be scaffolded by applying the framework on science textbooks, which are known to contain potentially problematic formulations (e.g. Treagust et al., 2003; Talaquer, 2007). This could support nuanced discussions about the relation between scientific language and expressions reflecting intentional and design stances, which may stimulate students' development in ways that are closed off by simply banning all anthropomorphic and teleological language use from the classroom (Zohar & Ginnosar, 1998).

Talanquer (2013) points out the need for more analysis of the assumptions and reasoning heuristics that underlie students' thinking in different contexts, which could serve to improve teaching and learning. Along these lines, further research could investigate the possibility of employing the framework presented here as one part of this development. Examples of interesting future avenues for research could be applying the framework to teachers' and textbooks' explanations of molecular phenomena. The framework could also be used to investigate language use in a wider variety of learners and types of learning materials, such as textbooks and animations. It is likely that other learning contexts and molecular systems might give rise to language use that differ in terms of the specific subcategories. Furthermore, molecular processes or phenomena may differ in how conducive they are to learners' inappropriate predictions based on the intentional stance. Therefore, the presented framework might need to be expanded as a result of future studies of learners' talk about molecules.

Limitations

The main limitation of the study is that the sample was relatively small and homogeneous. In particular, future work should consider including a wider range of student groups. The detailed findings in terms of the quantitative distribution of stances should therefore not be generalized to a wider population. In addition, it should be noted that the presented subcategories that differentiate between different types of usage of the three stances were developed in a particular scientific and methodological context. Therefore, the subcategories should not be viewed as the only possible ways of describing students' use of the stances. Future studies by other researchers with other groups of participants or a different scientific content may yield additional subcategories. Lastly, the analyzed data were collected in the context of investigating conceptual knowledge about self-assembly, and not students' language use in itself. Therefore, the data collection instruments did not specifically probe for students' reflections on their own usage of the three stances. Future work could investigate this to shed more light on the metacognitive aspects of students' molecular talk.

Conclusions

The main contribution of the present paper is to demonstrate that a framework from intentional systems theory (Dennett, 1989) can be used as an analytical tool for examining students' interpretive strategies in their talk about molecular processes. The findings of the study indicate that the three stances – intentional, design, and physical – may be differentiated and used for analysing students' language use. Together, the three stances and their subcategories represent explanatory strategies that range from purely physical descriptions of molecular processes, through structure-function analysis of molecular entities all the way through to interpretations of molecular events in terms of goal-directed actions performed by rational agents that have access to information about their surroundings.

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