Students' Communicative Resources in Relation to Their Conceptual Understanding—The Role of Non-Conventionalized Expressions in Making Sense of Visualizations of Protein Function

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The original publication is available at www.springerlink.com:

Carl-Johan Rundgren, Richard Hirsch, Shu-Nu Chang Rundgren and Lena Tibell, Students' Communicative Resources in Relation to Their Conceptual Understanding—The Role of Non-Conventionalized Expressions in Making Sense of Visualizations of Protein Function, 2012, Research in science education, (42), 5, 891-913.
http://dx.doi.org/10.1007/s11165-011-9229-2

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– the role of non-conventionalized expressions in making sense of visualizations of protein function

Introduction

There is a consensus in the educational research community that being able to reproduce a specific term is not necessarily the same as understanding the concept. Ausubel (1968) made an explicit distinction between *concept* and *concept word*. The concept word is connected to the concept via a convention (supported by a definition consisting ideally of a set of necessary and sufficient conditions) which is known throughout the community of scientific experts. Other means of referring to the concept may lack the authority of convention and the backing of a definition.

At the same time, there are also differences between perspectives on learning concerning what is meant by “understanding” a concept. While a cognitivist perspective on understanding would refer to the formation of cognitive structures and the ability of the learner to build connections between different concepts (e.g. Ausubel, 1968; von Glaserfeld, 1992), a socio-cultural perspective on understanding would refer to the ability of the learner to use the term in a socially meaningful way in a particular cultural context (Wertsch, 1995; Vygotsky, 1987). In our study, we use a semiotic approach to analyze language-based interaction and the formation of meaning and conceptual understanding, based on the theories of Grice (1957; 1989) and Naess (1966). We look closer at the relationship between the language students use when making sense of a set of visualizations of protein function, and their conceptual understanding of the visualizations.

A growing body of research in science education shows the importance of the use of different kinds of visualizations in relation to students' science learning (e.g. Gilbert, Reiner & Nakhleh, 2008). The purpose of any visualization to be used in an educational context is to facilitate learning and understanding of certain knowledge content. In order to accomplish this, a visual representation must make connections between knowledge the learner has and the knowledge content being taught (diSessa, 1982). This knowledge base for a given concept influence how the visualization will be interpreted and integrated into the students' knowledge base (Hiebert & Carpenter, 1992). In molecular life science, visualizations are essential for representing abstract and intangible entities such as DNA and proteins. In fact, images, diagrams and other forms of visualizations are playing increasingly important roles, not only in molecular life science teaching, and learning, but also as sources of information and instruments of analysis, modeling, and communication for the development of the research (Kozma, Chin, Russell, & Marx, 2000). However, studies of how students learn about proteins by using different kinds of visualizations are still sparse (Schönborn & Anderson, 2009; Authors, 2010). In this study we use visualizations of protein function as focus tools in interviews to investigate students' communicative resources and how they correlate to their conceptual understanding of the depicted processes.

Furthermore, we apply the Structure of Observed Learning Outcomes (SOLO) taxonomy (Biggs & Collis, 1982) as an analytical tool to categorize levels of complexity of the students understanding of the visualized processes.

The language of science and school science

The language used in science has been characterized as rational, abstract, and context-independent (e.g. Bernstein, 1964). The question is, however, whether this description fits the way spoken language is used by scientists and others engaged in scientific activities, or whether it rather describes a scientific ideal. Goodwin (1995; 1996) has shown that the language spoken by scientists in their day-to-day practice is highly context-dependent, and that gestures and deictic expressions (which are understandable only in relation to the context of the utterance, for instance “this” and “here”) make up an important part of scientific communication in the laboratory. Different uses of language in different contexts have been discussed extensively by Roth and his colleagues during the past decade. Roth and colleagues (Roth 2001; Roth & Bowen, 2001; Roth & Lawless, 2002) have stated that there is a progression in learning from physical manipulation of objects to gestures, deictic expressions and more and more elaborate and abstract spoken or written linguistic expressions. Early stages of linguistic expressions in science learning are characterized by what Roth and Lawless (2002) call “muddled” (vague) talk, supported by deictic expressions and iconic gestures. The muddled talk typical for beginners in a field also applies to scientists when they work in domains with which they are not very familiar (Roth & Bowen, 2001).

The communication in a certain situation, and how much can be learned from it, also has an emotive component. Milne & Otieno (2007) have studied the factor of students’ engagement in the context of science demonstrations, and conclude that students’ positive emotions and engagement in the demonstrations are important aspects of the possibility for meaning-making to take place in the classroom.

In an analysis of the process which can lead to regular meaningful conventionalized language, Grice (1957; 1989) makes a separation of meaning into natural and non-natural meaning. Natural meaning has some kind of non-arbitrary direct (causal) relationship to an event or phenomena – such as the tracks of a deer in the snow. On the other hand, non-natural meaning, which is more or less conventionalized, is always produced with some kind of communicative intention – for example, someone has indicated the trail with a series of broken branches. To be able to understand non-natural meaning, we must recognize the communicative intention of the speaker. In cases where non-natural meaning has been conventionalized we assume that the speaker's communicative intention conforms to the established conventional meaning of the expression, just as broken branches communicate a path to those familiar with the conventional meaning.

Although the language used in school science in many respects builds on scientific language, it differs from the language used by the scientific community. Furthermore, there is a difference between the language used by teachers and students. The subject-specific language used by a teacher contributes to the formation of a subject-specific language among the students. When a learner meets new, unknown, scientific concepts the only way to make sense of them is to relate them to previously known concepts, previous experience, and to formulate an understanding by using the scientific or non-scientific language and other communicative resources that he or she already possesses. A study by Brown and Ryoo (2008) showed that better learning outcomes occurred when the instruction was first given using everyday language to explain the scientific content and then scientific language was introduced, rather than the other way around.

During the last decennia, science education research has gathered a large body of empirical data concerning students' ideas about scientific concepts (Duit, 2008). Duit points out that student conceptions can differ from the concepts taught in school science. In science education it has been found that students use everyday concepts or terms to express their scientific ideas, especially when dealing with concepts concerning microscopic or sub-microscopic phenomena (e.g. Author, 2007). This study focuses on investigating how students use language, normal everyday conventional, non-conventionalized, and scientific, to express scientific concepts.

In a discussion of the relation between concept and concept word, Naess (1966) claims that there is often a difference in what he refers to as *depth of intention* in the statements made by an expert compared with the "same" statements made by a novice. This means that although they may use the same terms, the underlying meaning (conceptual depth) is more extensive and richer in the language of the expert than in the case of the novice.

Research on the development of expertise, i.e. Dreyfus and Dreyfus (1986), indicates that experts tend to be less restricted by pre-formulated rules in seeking solutions that accord with a specific situation. The explanations created by the expert are generally based on his or her experience, and are constructed from a match between the features of a specific problem or situation and the expert's databank of earlier problems and solutions that have proved to be successful (Björklund, 2008). In relation to the use of standard scientific terminology, this means that whereas students can sometimes (or even often) use scientific terminology with little conceptual depth or depth of intention, experts can sometimes convey a very well developed and refined conceptual understanding in words or expressions that on the surface seem to lack a definite or determinate depth of intention.

The analysis of communicative resources

In the analysis of meaning of scientific terms it is necessary to make a distinction between *vagueness* versus *precision* on the one hand, and *generality* versus *specificity* on the other (Naess, 1966). Terms belonging to everyday natural language tend to be vague and more or less general or specific in meaning. The same term occurring in a scientific context is used with a greater degree of precision. The precision of a term relates to how well-defined the term is in relation to other terms that could be used to refer to a group of phenomena. The definition delimits the range of interpretations and applications of the term. Ideally, a precise meaning of a term eliminates the uncertainty of borderline cases. How general the meaning is for a particular term relates to how many of the phenomena in question can be referred to using the term. If the term can be used to refer to all the phenomena, then the term is totally general. Usually, however, there are a number of less general terms (more specific terms) that cover various sub-areas of the range of phenomena in question.

To illustrate, the analytical approach is exemplified with a concept from the discipline of chemistry (see Figure 1). If we take the word “bond” that occurs in both everyday language and the language of the sciences, we can make a four-way distinction between vagueness and preciseness, and generality and specificity as depicted in Figure 1. In the figure, the everyday word “bond” can be used in a vague and general sense to cover a wide range of references, some of which border on pure ambiguity (homonymy). The expression “interpersonal bond” refers to a specific type of phenomena covered by the term “bond” but not necessarily adding any precision to the term. The term “bond” is still as vague as it was in the general case. In order to move in the direction of precision, what is needed is a regulation or regimentation of the term by a definition. One case of this is the use of the term in connection with atoms and molecules, where the term “chemical bond” refers to a certain class of phenomena in nature, covering different types of electrochemical forces between particles, such as ionic bonds, covalent bonds and Van Der Vaal bonds. In this case, the term “bond” has been explicitly defined. Using the precise expression “covalent bond” we can refer to a specific type of chemical bond. It is important, if not absolutely necessary, that communicators know to which area of the figure the term “bond” belongs in order not to misunderstand or mislead each other. Confusing the vague and general sense of “bond” with the precise and general can result in the creation of analogies that are misleading and irrelevant in a scientific context. The scientific term “bond” has its roots in the everyday word “bond”, of course, but should not be identified with it. In the communicative practice of science, the scientific term has taken on a much more precise and general meaning. Of course, we need to be able to use the term with different degrees of vagueness, precision, specificity and generality in different contexts and cultural settings. In fact, the rubber-like traits of the vague expressions of everyday language help us to communicate certain meanings we want to convey. A consistently precise use of language, regardless of cultural context, is not something to strive for.

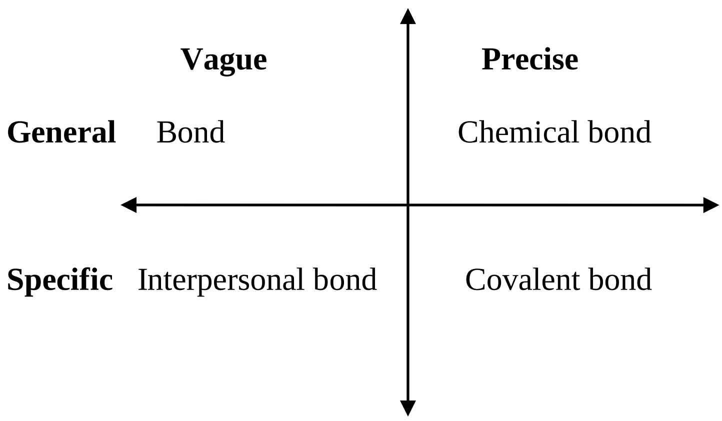


Figure 1. Model showing how the term ‘bond’ can be used with varying degrees of preciseness and specificity (Authors, 2009).

SOLO-taxonomy and conceptual depth

Since we are interested in investigating how students understand protein function, we need to have an idea of the conceptual depth of this understanding. Although Naess (1966) does not suggest any classification system for different levels of depth of intention, he indicates that depth of intention is a gradual concept, which could be described at different levels of conceptual depth. In the international literature on assessment of learning, several systems of evaluating learning outcome have been proposed. In our analysis, we chose the SOLO-taxonomy (Biggs & Collis, 1982) as a framework for categorizing the different levels of conceptual understanding (depth of intention) of the students’ responses in the interviews. The SOLO-taxonomy describes levels of complexity in a student's conceptual understanding of a subject, through five levels, and it is claimed to be applicable to any subject area. At the first level, the *pre-structural*, the students are simply acquiring bits of unconnected information, which have no organization and make no sense. At the second level, the *uni-structural*, simple and obvious connections are made, but their significance is not grasped. At the third level, the *multi-structural*, a number of connections may be made, but the meta-connections between them are missing, as is their significance for the whole study object. At the fourth level, the *relational*, the student is now able to appreciate the significance of the parts in relation to the whole. Finally, at the highest level, the *extended abstract*, the student makes connections not only within the given subject area, but also beyond it, and is able to generalize and transfer the principles and ideas underlying the specific instance.

The research purpose and questions

The purpose of this study is to investigate the relationship between students' use of terms and their conceptual understanding of protein function via visualizations. The research questions include: (1) How do students express their understanding of visualizations of protein function? (2) What is the relationship between students' use of terminology and their conceptual understanding? (3) Does the use of conventionalized and non-conventionalized expressions differ among different educational levels and among the students and the experts?

Methods

In this section, the research design and instruments developed and adopted in this study are described. Since three visualizations served as important tools in exploring participants' language use in explaining their understanding of protein functions, a characterization of the visualizations used in this research is especially addressed. Futhermore, the participants' background knowledge and our method for analyzing the data are described.

The research design and instruments

A qualitative research approach was adopted in this study. Through semi-structured interviews, the participants were asked about their interpretation of two diagrams of protein function (redesigned from examples in text books used in upper secondary biology and chemistry courses), shown in Appendix I, and one animation illustrating water transport across a membrane (http://nobelprize.org/chemistry/laureates/2003/animations.html). The visualizations used in the study were chosen with an intention to show biomolecular processes in the cell, in which protein function is a central aspect. We chose two processes that are well-described and visually depicted in upper-secondary biology textbooks, transport across the membrane and protein synthesis. The reason to have both still images and animation in our study was to avoid the bias that might be generated due to the different formats of visualizations. The conceptual understanding in relation to the formats of visualizations is not discussed in this study, but presented in another paper we have published (Authors, 2010).

The visualizations were used as focus items in the interviews, eliciting free responses from the interviewees. The questions posed by the interviewer mainly aimed to make the interviewees clarify their responses. The interviews, which can be described as revised clinical interviews (Kvale, 1996), lasted about 45 minutes each. In the interviews, all participants were shown the same visual representations and were asked to use their prior knowledge to interpret the visualizations. They were not given any specific information about the visual representations. The choice of using of this kind of semi-structured interview was based on our intention to study the use of language and conceptual understanding of individual students in their interaction with the visualizations. The individual interview format made it easier to analyze individual students' use of language and conceptual understanding than group interviews or studies of classroom talk.

The interviews were conducted according to an interview guide that highlighted certain topics of interest (see Appendix II). Each interview consisted of five phases: a briefing phase, a warm-up phase, the main phase, an end phase, and a debriefing phase. In the briefing phase, the project and interview procedure were explained. After the briefing phase, the MP3-player was turned on. During the warm-up phase, general questions about the participants' experience of science in and outside school/university were posed and the conversation began to home in on the main topic. In the main phase, the visualizations were shown and the participants were asked to explain what was depicted by them. Finally, during the debriefing phase, the MP3 player was turned off and the participants were given the opportunity to alter his/her statements and to ask questions. All the participants were informed about the purpose of the interview and have signed informed consents. Each interview was audio-recorded and transcribed in full. In this article, we only analyze the main phase of the interviews.

Characterization of the visualizations used in the study

The following paragraphs briefly describe the content presented by the visualizations used in the interview study. All the visualizations are highly simplified representations of proteins that are intended to illustrate common functions of proteins rather than their structure. The two diagrams (see Appendix I) used in this study are generalized descriptions of principles of processes, rather than examples of the functions of individual proteins. In the case of the animation of the channel protein (aquaporin), the shape of the protein has been constructed from the determined 3D structure of aquaporins and the dynamics according to thermodynamic calculations.

Visualization 1 shows a cross-section of a cell membrane (see Appendix I). The cell membrane consists of a bilayer of phospholipids, each of which has a polar part (which collectively form the inner and outer surfaces) and a non-polar part (which constitutes the interior of the bilayer). The phospholipid bilayer also contains other molecules, primarily proteins. The membrane should be considered a dynamic structure, in which molecules are continuously moving, changing places and sometimes moving into and out of the membrane. However, this dynamism is not conveyed in the visualizations. The membrane functions (*inter alia*) as a barrier that protects the interior of the cell from its surrounding environment. Small, uncharged molecules can readily move through the membrane without aid (via “passive transport”), while charged and large molecules are “locked out”: phenomena that are not shown in the visualizations. However, appropriate metabolites must be taken into cells and waste products removed. Much of the complex structure of biological membranes is therefore involved in the regulation of such transport. The intended meaning of Visualization 1 is to illustrate the principles of three modes of transport of small molecules across a biological membrane, mediated by the three proteins acting as channels or pumps shown in red. Various substances flow into or out of the cell in a controlled manner through proteins such as these. The protein to the left illustrates a channel that facilitates transport of a substance (shown in grey), that diffuses in the direction of its concentration gradient. The middle protein mediates transport of specific molecules, also in the direction of their concentration gradients. The protein to the right is an active transporter, which transports molecules against their concentration gradient, in a process coupled to energy generated by the breaking of bonds in ATP molecules (“active transport”).

Visualization 2 (see Appendix I) shows the processes of transcription (RNA synthesis) and protein synthesis in the cell, starting with the transcription of DNA into three types of RNA in the nucleus (shown in blue). All three types of RNA are transported out of the nucleus, through the nuclear envelope, and out into the surrounding cytoplasm. The messenger RNA (mRNA) molecule (which carries the code for a corresponding protein) binds to ribosomal subunits, and the transcription is started (shown at the right hand bottom of the picture). The other two types of RNA also have functions in protein synthesis. The ribosomal RNA (rRNA; shown to the right of the mRNA molecule), is an important constituent of the ribosomal subunits together with certain proteins, while transport RNA (tRNA; shown at the top of the picture) transports the various amino acids to the ribosome. There are multiple species of tRNA, each of which has an “anticodon” (three bases shown at the top of the molecule shown), which matches a specific amino acid. The tRNA molecules bind to the mRNA molecule in the ribosome in an order specified by matches of the sequence of bases in the mRNA to the tRNA’s anticodons. The amino acids thereby transported to the ribosome are connected to a growing polypeptide chain, which eventually forms a functional protein. The information contained in the DNA is thus expressed in proteins, with mRNA acting as a mediator.

The animation illustrates the facilitated transport of water molecules through a channel protein in the cell membrane (aquaporin) according to findings by Agre, who was awarded the Nobel Chemistry Prize in 2003 (Agre et al., 1993; De Groot & Grubmüller, 2001; Tajkhorshid et al., 2002). The animation, which can be viewed at http://nobelprize.org/chemistry/laureates/2003/animations.html, shows a large number of diffusing and colliding water molecules. To make it easier for the spectator to follow the route of the transport of water molecules through the aquaporin (displayed in cross-section), one of them is marked yellow.

Participants

Two groups of students, from upper secondary school and university level in a medium-sized town in southern Sweden, were invited to participate in this study. The thirteen (ten girls and three boys) participating upper secondary students (from two schools) were in their second (grade 11) or third (grade 12) year of the natural science program or the combined natural science/social science program. Four university students (two girls and two boys) were attending the third year of their tertiary education, majoring in chemical biology. The

university students had relatively uniform background knowledge, while the upper secondary students had studied various combinations of natural science courses, and consequently differed in their pre-knowledge to a relatively high degree. Furthermore, two experts (university professors in molecular life science, one male and one female, each having ten years of experience or more of teaching the topic) were interviewed. All students were interviewed individually. The two experts were, however, interviewed together.
The students and experts were interviewed using the two diagrams (Appendix I) and the animation as focus items.

Data analysis

Our data consists of interview transcripts of the students' interpretations of the two forms of visual representations (two diagrams and one animation). The reason to have both still images and an animation in our study was to avoid any bias that might be generated due to the different formats of visualizations. In this study, we did not analyze differences in the students' interpretation of the two different forms of visualizations, since that is the focus of another study (Authors, 2010). The transcripts were first analyzed iteratively according to the method of analytical induction (Abell & Smith, 1994); they were read and coded individually by two senior science educators followed by a discussion to reach a consensus. After coding the participants' responses, the use of communicative resources to describe the three visualizations were analyzed in relation to the participants' conceptual depth (the five levels of SOLO-classification). The results were analyzed through a descriptive statistical analysis of conceptual depth and communicative resources.

The participants' degree of conceptual depth in connection to the visualizations were evaluated and categorized into a scoring system based upon the SOLO-taxonomy (Biggs & Collis, 1982).

In terms of the participants' conceptual depth, we gave scores from 1 to 5 according to the SOLO-classification levels 1 to 5. We then calculated each participant's average scores gained from the three visualizations and divided them to 5 and got the percentage of their conceptual depth. Accordingly, all the quantitative results are presented by percentages in this study.

The interviewees' statements in their explanations of the content of the visualizations were analyzed focusing on the students' use of communicative resources. This analysis occurred in several phases. The first phase resulted in the identification of three categories of expressions, *subject-specific expressions* (defined as scientific terms appearing in the students' textbooks), *deictic expressions* (like "here" and "that"), and *non-conventionalized expressions.* In a second phase of the analysis statements referring to the different categories were colour-coded. In the last step of the analysis, the colour-coded words were evaluated in terms of their relationship to the context of the interview and whether or not they were part of a scientifically meaningful explanation. From the results, we also identified some other everyday expressions (i.e. metaphorical expressions) among the participating students, which have been focused in an earlier publication (Authors, 2009) and are not discussed in this article. We calculated the number of times each category of expression (deictic, non-conventionalized and subject-specific expressions) was used and transferred the occurrence of each expression (from the total three visualizations) into percentages by dividing these by the total numbers of expressions.

Results

A first and expected observation is that the conceptual depth of students' knowledge appears to increase with educational level (Figure 2). According to the SOLO-classification, none of the upper secondary students in this investigation reached a higher level of depth of conceptual understanding, for any of the visualizations, than a multi-structural (SOLO 3) and sometimes partially relational (SOLO 4) level. Furthermore, some important aspects of protein function and interactions between molecules were not included in either the upper secondary or tertiary level students' explanations. Notably, the students did not formulate their responses in terms of electrochemical interactions between molecules. An expert-like awareness of and familiarity with the electrochemical properties of the molecules involved seems to be difficult to attain, even at university level.

In the interview transcripts, we observed several examples of responses indicative of difficulties with interpreting the visual representations. Several students interpreted simplified visual representations highlighting a certain process as giving a quite realistic description of the depicted events. Other interpretation problems were related to lack of prior knowledge about the scientific concepts involved and the conventions associated with reading diagrams and animations, especially amongst second-year upper secondary students.

The example below shows the definitions of conceptual depth developed according to the SOLO-classification for the visualization of protein synthesis (See Visualization 2 in Appendix I) and quotes from the students serving as examples from each SOLO level. Since none of the participating students reached the highest SOLO level in their reasoning with this visualization, we could not include any student quote to illustrate level five. "I" stands for the interviewer.

Level 1 Pre-structural: no coherence. Some abstract terms are used by the student, but without consistency.

SY201: *I don't remember the name of this.*

I: *It doesn't matter.*

SY201*: But… mm… it shows how copying of DNA is made, doesn't it?*

I*: Hm… what is produced in this process?*

SY201*: Eh… RNA?*

Here, the student fails to recognise the process of protein synthesis and what is the outcome of the process. She uses some scientific terms, but applies them more or less randomly.

Level 2 Uni-structural: simple mechanical description. The student exhibits a certain amount of coherence in the description of the process, but there are major inconsistencies regarding the result of the process and how it connects to other cellular processes and to the functions of proteins. For example, the spatial positions of the nucleus, RNA-molecules and ribosomes are unclear.

SY306: *Yes, first it [the DNA helix] breaks up. Then there is the mRNA that comes and copies it. And then it is transported out of the cell. But, yes, it is restructured… what is it called… translation, or transcription… no, I think it is translation first, then it transcripts it self out in some kind of way and then it is put together in long chains in the ribosome, which in its turn puts the proteins together, which carry out the commandos of the gene itself.*

Here, the student provides an explanation of the process that is only partly possible to follow. He shows major inconsistencies in his reasoning, and several processes are mixed up, not only relating to mix-ups of concept words, but also to mix-ups of content. However, he manages to explain one part of the process, the translation of the genetic information into proteins at the ribosome relatively consistently.

Level 3 Multi-structural: mechanical description. The result of the process is clearly stated by the student, but inconsistencies remain about its connection to other processes and to the functions of proteins. The spatial positions of the nucleus, RNA-molecules and ribosomes are clearer.

> SY302: *There are three different kinds of RNA, you see it here… tRNA, eh… messenger-RNA and the ones that fetch… tRNA… they fetch different amino acids and put into the ribosome where the mRNA comes in. There are specific places where they can sit…*

Here, the student exhibits a more coherent overview of the components and the end-products of the process. However, some inconsistencies relating to the different components and their function remain.

Level 4 Relational: advanced mechanical description. The result of the process and its connection to other processes are clear in the student's description, and connections are made to different functions of proteins. The spatial positions of the nucleus, RNA-molecules and ribosome are clear.

> U301: *These tRNA are specific… a specific tRNA that has this anticodon there… it has a specific binding site for a certain amino acid… then it enters the ribosome and then the anticodon binds to this place on the mRNA [I:Mm] which has… yeah, these basepairs here and then the last tRNA which comes in next to it and then these amino acids bind to each other, forming this chain… and then the whole ribosome divides and this [points to the growing protein chain] goes away.*

Here, the student gives a coherent description of the process, its end-products and the functions of the different components involved. However, she does not relate it to other processes in the cell.

Level 5 Extended abstract: dynamic description. Based on an understanding of the electrochemical properties of the molecules involved, the student exhibits an awareness of the complexity and dynamic character of biomolecular processes. The student shows the ability to think in three dimensions and to switch between different representations.

The participants' interpretations of the three visualizations

Regarding Visualization 1 (see Appendix I), depicting membrane transport, 8 out of 13 upper secondary students and all four university students could interpret parts of the meaning and distinguish between the three different types of transport through a biological membrane. The majority could also appreciate, for example, the significance of the concentrations of molecules on each side of the membrane. However, five of the upper secondary students merely recognized some of the symbolic features or drew only simple or obvious conclusions.

Regarding Visualization 2 (see Appendix I), depicting protein synthesis, 9 out of 13 upper secondary students showed a conceptual understanding at the multi-structural level (SOLO 3) and could make some connections between the components and processes in the visualization, but the significance of each of them, the multidimensional pattern between them, and the significance of the whole were missed. Three upper secondary and all university students were able to make such connections at the relational SOLO-level (SOLO 4) and all students appeared to at least have an understanding of parts of the process or a superficial understanding of the whole.

In the animation of water transport through a cell membrane, eight of the upper secondary and three of the university students were able to understand the message of the animation at the multi-structural level (SOLO 3) or higher, while the remaining five upper secondary and one university student had problems understanding what process the animation depicted.

The upper secondary students generally showed a more even distribution of understanding of the visualization regarding protein synthesis than of the other visualizations, and there were relatively wide spreads in their understanding of the visualizations of transport through the cell membrane. However, in some cases, some of the difficulties associated with the latter visualization were due to the fact that the student concerned had not been taught about transport through the cell membrane. In fact, protein synthesis is generally taught at the second year of upper secondary education, while water transport across a cell membrane is taught during the third year of upper secondary school. The university students generally had no problems in interpreting scientific content in the diagrams, although in a few cases they attributed the wrong content to the visualization.

Participants' communicative resources and conceptual depth

The terms used by the participants and the levels of conceptual depth are presented in Figure 2. It was not surprising to find that conceptual understanding increased with level of education, and the two experts showed the highest level of conceptual depth. It seems that the use of deictic terms (e.g. this and there) decreased with level of education. However, it is interesting to find that non-conventionalized terms were used by upper secondary and tertiary students and continued to be used in the expert group. Also, in the group of second-year upper secondary school students, it was found that conceptual depth was not correlated to the frequency of scientific terms used (see Figure 2).

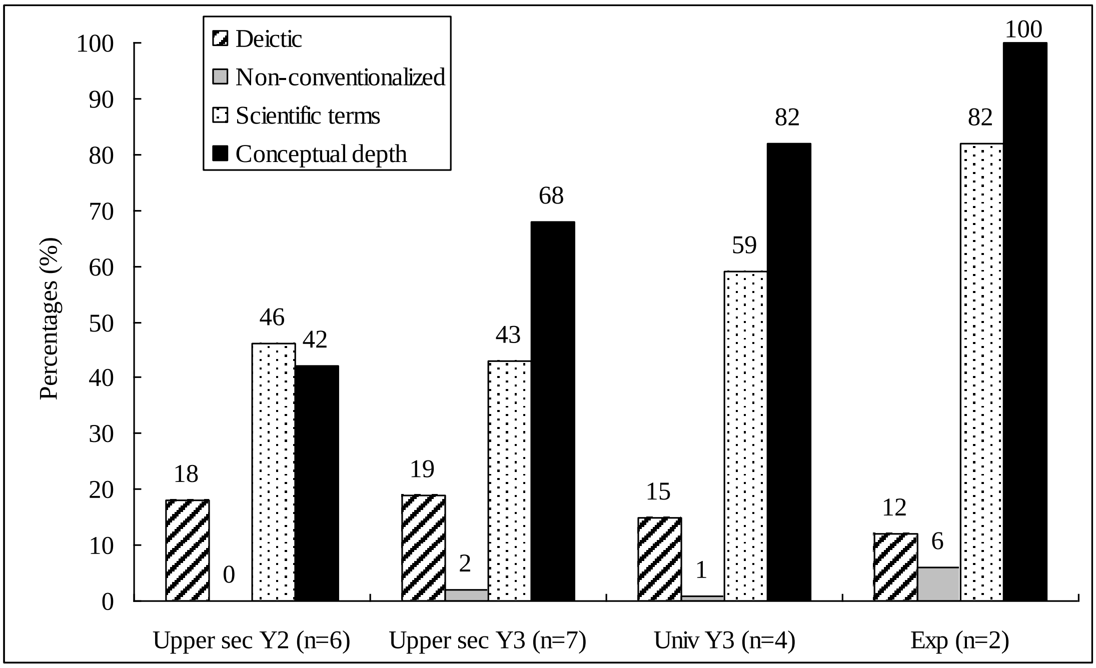


Figure 2. The relative frequency (%) of use of the three categories of expressions: deictic expressions, non-conventionalized expressions, and subject-specific expressions (scientific terms) by the students and experts taking part of this study as compared to the levels of conceptual depth achieved in their explanations of the visualizations in the interviews.

Examining the frequency for each group, Figure 2 shows that the scientific terms dominate in the students explanations and increase with educational level. The category ‘deictic expressions’ comes second and is relatively stable among the student groups, varying between 10-20% of the "vocabulary". These expressions are also totally dependent on the presence of the visualizations in the context. Although the non-conventionalized terms were used with a low frequency, it is important to note that they form a part of the meaning-making process. The results presented in Figure 3 also indicate that there was little discernable co-variation between the conceptual depth and the use of scientific terms or non-conventionalized expressions among the students. Especially among the students from the second year, but also from the third year of upper secondary school, students’ understanding of the scientific content is not positively correlated to the frequency of scientific terms they used in their explanations. For example, students SY204 and SY306 (see quote from this student exemplifying SOLO level 2) are some of the students using the highest proportion of scientific terms among the upper secondary students and at the same time has one of the lowest levels of conceptual depth while student SY304 uses in comparison relatively few scientific terms and still appears to show high degree of conceptual depth. However, this phenomenon was not found among university students.

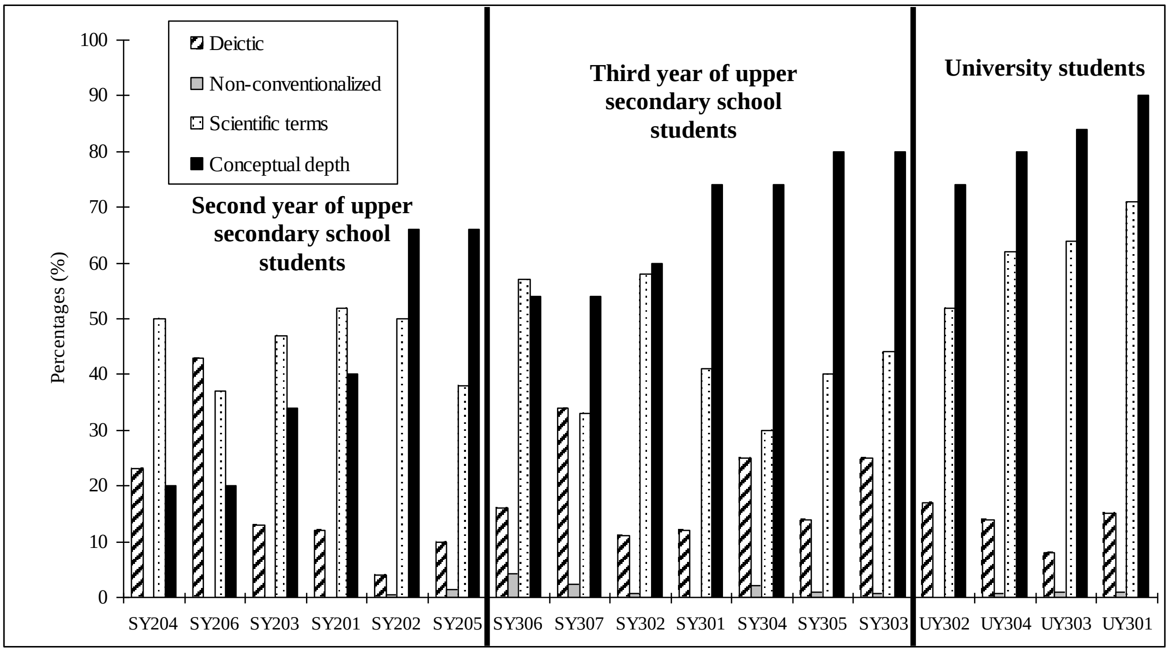


Figure 3. The relative frequency (%) of use of the categories of deictic, non-conventionalized and subject-specific expressions (scientific terms) by all the 17 participating students as compared to the levels of conceptual depth achieved in their explanations of the visualizations in the interviews. The sequence corresponds to the percentages of conceptual depth (from lower to higher) in each group of students.

Non-conventionalized terms in communication of science

The analysis of the participants' talk in the transcribed interviews showed that several participants used words which lacked a clear conventional meaning or denotation. Although lacking a conventional meaning, these words were not used randomly. They were used by the students and experts with a specific, context-bound meaning. Furthermore, there seemed to be a certain degree of conformity in the way the expressions were used. Examples of non-conventionalized expressions in Swedish used by the interviewees in the investigation are “plupp”, “flopp”, “blubb” and “klutt” which, out of context, seem to bear only an extremely vague meaning or even no meaning at all.

Despite the fact that the non-conventionalized words are a marginal part of the vocabulary used in the students explanations we find them important to analyze more in depth. Firstly, more than half of students and both experts use them, some only once and others more often. Secondly, they appear not to be arbitrarily used but bear rather specific meanings.

In the interview material, non-conventionalized expressions are used by the students to describe different molecular structures and processes, although only occasionally compared to their use of scientific terms (Figure 3). However, one upper secondary student used the word “plupp” on four occasions during the interview, referring to different structures in the cell. In all instances the word “plupp” was used to depict small, compact structures, such as symbolic representations of water molecules, nitrogen bases, and the water-soluble part of phospholipid molecules in a cell membrane shown during the interviews.

In the first example, SY304, a student in her third year of upper secondary studies, is shown the visual representation of the process of protein synthesis. To describe the conformational change in DNA at the beginning of transcription, she makes a metaphoric association to a ball of wool. At the end of the quote, she replaces the term “nitrogen bases” with the non-conventionalized term,”floppar”.

I: Do you recognize this picture? Do you know what it represents?

SY304*: Yeah.... it’s DNA, transcription and stuff...*

I: Yes, quite. Could you tell me what's happening? If we start here, with the DNA in the nucleus, can you tell me what happens here to begin with?

SY304*: Hmmm, I'll have to think.... to begin with, it's all wrapped up like a ball of yarn, and then it folds itself up, I think.*

I: Do you mean the DNA?

SY304*: Yeah, the DNA…[...] This codes for amino acids, like, three pieces like this [points to the mRNA-molecule],* ***floppar,*** *[laughs] become an amino acid. And these amino acids are joined together to form a long chain in a protein.*

In the second example, SY305:, also in the third year of her upper secondary studies, is shown the same visual representation as SY304 above and explains – correctly – that the order of the nitrogen bases on a transportRNA molecule determines which amino acids will be added to the growing protein in the ribosome. However, she replaces the term,"nitrogen base", with the non-conventionalized term "pluppar".

SY305*: It's a sort of chain that has these little* ***pluppar*** *that the mRNA recognizes and binds to in the right place, so that the protein…*

I: I see... Can you elaborate on that?

SY305*: Every one of these things that the amino acids bind to has a special code of some kind [I: Mm] that is specific to a particular amino acid....*

In the third example, one of the experts uses a non-conventionalized expression to describe the color-code used in the same visualization to represent the different kinds of nitrogen-bases on the RNA molecule.

Ex_1: *And then there is some kind of color-****blupp*** *code for each RNA…*

In the fourth example, the other expert refers to the aquaporin protein in the animation by using a non-conventionalized expression.

> Ex$_2$: *Yes, 'cause I don't know even at upper secondary level, I wonder whether they see that it is a protein… a grey* **klutt** *of dough…*

SY304 uses the word "floppar" to depict the nitrogen bases of a transportRNA molecule. The same structure is referred to as "pluppar" by SY305. These non-conventionalized expressions thus seem, at least, to have partly overlapping meanings. Both students make use of these words in the context of reasoning that shows that they possess a conceptual understanding of the scientific content – i.e. that the genetic code refers to the order of nitrogen bases in DNA, which determines the order of amino acids in a protein, and that the information in the genetic code is transferred from DNA via RNA to proteins. Even if they seem to be aware of the identity and functions of nitrogen bases, they both seem to have trouble remembering the proper scientific term. However, by using non-conventionalized expressions, they can still show that they have grasped the central conceptual content of the visual representation.

It is a striking feature of the interview transcripts that the students actually reason – often together with pointing gestures - in a way that shows that they have grasped important aspects of the scientific content, at the same time as they have difficulty in using the proper scientific terminology.

Analyzing non-conventionalized expressions

Grice's (1957, 1989) theory of natural and non-natural meaning may help us to understand how we can interpret non-conventionalized expressions through a familiarity with the context of the utterance and our grasp of the communicative intention of the speaker. We are normally able to understand what a speaker means by the non-conventionalized expression "plupp" relying on our knowledge of the context of the utterance and do not pay any special attention to the fact that the speaker uses a non-conventionalized expression and not the correct term. Gestures such as pointing and deictic expressions also enable us to immediately grasp the meaning of such non-conventionalized expressions. In the case of non-conventionalized expressions, it is essential for the listener to understand what the speaker intends to say, given the context and objects present and not only the verbatim meaning of the words (which is actually absent). Grice's non-natural meaning does not require conventionalized words or linguistic expressions. Even non-conventional or spontaneous innovations can function as expressions of non-natural meaning as long as the communicative intention of the speaker can be reasonably recognized by others.

In an investigation of the context in which a term (conventional or non-conventionalized) is used, it is possible to discuss the range of meaning, i. e. the specificity and generality respectively the vagueness and preciseness of the term. Let us look more closely at the term "Nitrogen base" as used by the scientific community and the term "floppar" used by the students.

The term nitrogen base refers to a certain chemical compound that is a constituent part of the DNA and RNA molecules. There are four types of nitrogen bases in DNA and RNA respectively, and their order determines the genetic information conveyed in the molecule. In a scientific context, the concept of nitrogen bases as chemical compounds and their function in the biochemistry of life is well established and defined. Therefore, the meaning of the term "nitrogen base" is general - it always refers to all entities of a certain kind - as well as precise (meets explicit criteria) - the referents are clearly defined, and there are no borderline cases (see Figure 4).

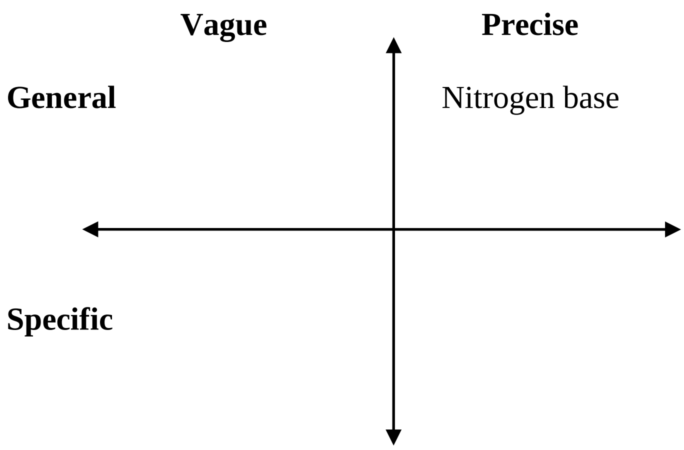


Figure 4. The model in Figure 1 applied to the scientific term “nitrogen base”, as it is used by the scientific community.

SY304 uses the non-conventionalized expression “floppar” as a place-holder for “nitrogen bases” in her explanation of how the genetic information is transferred from DNA to proteins via RNA. To be able to interpret “floppar” as meaning “nitrogen bases”, the listener must have a thorough understanding of the context of the utterance and the visualization to which she refers. Therefore, the range of meaning of the word “floppar” is specific rather than general (see Figure 5). Hence, the apparent nonsense-word “floppar”, in the contextual use of SY304, is actually to some degree precise (notice the vector arrow in Figure 5), in that the group of referents – nitrogen bases – is possible to identify. However, this specific and partially precise meaning is restricted to the context and relies on the visualization. The preciseness is dependent on her conceptual pre-knowledge about how the genetic information is transferred and the recognition of her intention to communicate a specific and precise conceptual understanding.

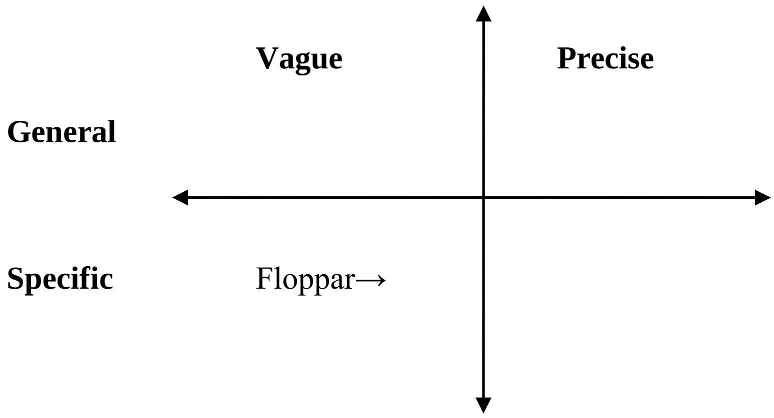


Figure 5. The model in Figure 1 applied to the non-conventionalized expression “floppar” (not translated into English, as there seems to be no equivalent), referring to “nitrogen bases”.

Viewed in an actual context of use, non-conventionalized expressions function as deliberate precisification and specification devices for naming and characterizing an object or process for which the speaker has no usable name.

Taken out of context, or when they are to be interpreted by someone not familiar with the context, the non-conventionalized expressions may be viewed as extremely vague or even meaningless. All expressions (even scientific terms) may, of course, be regarded as vague to a certain degree. However, in the case of non-conventionalized expressions, what counts as problematic vagueness when viewed out of context, is, in context, rather a fundamental defining trait. When speakers make use of non-conventionalized expressions, their - conscious or unconscious – aim is to give a specific and precise characterization of a certain phenomenon although they are unfamiliar with the proper terminology for the area, and therefore reluctant to give an exact scientific term which might possibly lead to an incorrect interpretation or characterization. The usefulness of non-conventionalized expressions lies in their chameleonic ability to take on new specific and also precise meanings in new contexts.

In the long run however, the students need to learn how to buy into the precision and generality of the scientific terms which their non-conventionalized expressions lack and to be able to make themselves understood in contexts where their explanations may rely less on the details of a particular visualization.

Discussion

While acknowledging that when studying learning, we do not only need to take the cognitive aspects in account; behavioural and emotional engagement are also important (Milne & Otieno, 2007), however, for this study our focus was on aspects of cognition and language use by individuals. Since context-dependent language has been found among scientists and students (Roth 2001; Roth & Bowen, 2001; Roth & Lawless, 2002), our study was conducted with a focus on analyzing students' and experts' language use in a context of interpreting visual representations of protein function.

The results of this study indicate that there are different expressions that could be identified in the participants' descriptions of visualizations of protein function. The major findings of this study (however, bearing the small sample size in mind) are that the use of scientific terms are not necessarily correlated to participants' conceptual depth, and furthermore, that non-conventionalized expressions were used by both groups of students as well as by experts. This research also shows that visualizations can be a useful tool in exploring students' use of language in in relation to their conceptual understanding.

There seems to be no clear connection between the use of scientific expressions, non-conventionalized expressions and the depth of conceptual understanding of scientific content (see Figure 3). The results also indicate that students may use subject-specific expressions (scientific terms) to a high degree, without having a deep understanding of the content (Figure 3). Furthermore, students may have a deeper understanding of the content, while not being able to express this understanding using subject-specific expressions (scientific terms). For some students, non-conventionalized expressions may be a way of communicating an actual understanding without using the subject-specific terminology, provided that the context contains visualizations, for example. We take this to be a very important finding for science educators. These findings give further support to the conclusions of Brown and Ryoo (2008) to encourage teachers to make use of students' non-scientific expressions and that everyday language is a valuable resource in the students' struggle to come to terms with scientific concepts and terminology.

A term may have a different conceptual depth and a different meaning for teachers when compared with students. Therefore, students' use of everyday words or spontaneous non-conventionalized expressions to denote a precise conceptual understanding may possibly be understood by the teacher as a sign of lack of understanding, due to the vagueness of the expressions used by the students. But the empirical findings presented in this study (e.g. the statement of SY304) indicate that the students' use of non-conventionalized expressions – when lacking the ability to express themselves by using conventional terminology (scientific terms) – may obscure the fact that they actually have acquired an understanding of the scientific content.

In our data, deictic expressions were used to approximately the same degree by all the different groups. This may be connected to the presence of the visualizations in the interviews, which makes it easier to refer to an object or process by a deictic expression or a non-conventionalized expression than by using standard scientific terminology. Using the visualizations as a tool to fascilitate communication, together with non-conventionalized expressions and deictic expressions, the students were often able to give a satisfactory description in general accordance with a scientific understanding of the phenomenon, relative to the learners' levels of education.

Non-conventionalized expressions and conceptual understanding

Non-conventionalized expressions may exist in several other learning contexts (Author, 2006). However, the use of non-conventionalized expressions as a tool for handling new objects in speech becomes especially evident in an abstract discipline such as molecular life science with a wealth of complex concepts and where use is made of subject-specific visualizations for objects that most people never encounter in their everyday lives. The ability to understand information conveyed by visual information is central to the life science area. To demonstrate that they understand the scientific content, the students need to be able to interpret the structures and events conveyed by the visualizations and crucially – at least in school examinations – to express the intended meaning using language. Our results seem to indicate that in many cases the student's problem may not be to understand the visualizations and to think "visually", but rather to reformulate this understanding into a subject-specific conventionalized language.

An interesting result is that the students made use of non-conventionalized expressions, which seem to belong to more informal language (as probably indicated by SY304's giggle when she says "flopparna"), in the more formal interview situation. Our interpretation is that the vagueness of the non-conventionalized expression enables the students to express an explanation without using a scientific term, the proper usage of which they are unsure of or simply do not remember. Furthermore, these words make the statement more open, allowing the interviewer/teacher to fill in with his or her own knowledge to make a positive interpretation and to give a more general characterization of the specific phenomenon referred to by the student's expression together with the proper scientific term.

Non-conventionalized expressions like *plupp* and *flopp* may not appear in standard lexica of the Swedish language; however, they are used by Swedish-speaking people in different contexts, also in the science classroom. In future studies, it would also be interesting to study the use of language in a more “natural” context, such as classroom discussion, where the occurrence of non-conventionalized expressions could be studied.

From novice to expert in molecular life science

The non-conventionalized expressions used by the students in this study, may be categorized as a form of ‘muddled talk’ in the terminology of Roth and Lawless (2002), typical of a learner who has not yet mastered the scientific language. However, this would not be an accurate description of the language used by the two experts. Interestingly, the two experts interviewed used many words that could be classified as non-conventionalized expressions (words like *blubb* and *klutt*) in their explanations (see Figure 2). In this case, there is no doubt that the experts were very well aware of the precise meaning of the scientific content conveyed in the visualizations. Still, they seemed to use non-conventionalized expressions more than the university students, who seemed to be more anxious to use proper scientific terminology. At the same time, the experts used a relatively higher percentage of subject-specific expressions. It is possible that these non-conventionalized expressions may constitute a part of their professional jargon (see Goodwin, 1994). This would accord well with the findings of Dreyfus and Dreyfus (1986), that experts tend to be less restricted by pre-formulated rules, and freer to find solutions (or formulations) that accord with the specific situation rather than with any pre-formulated system of rules.

It is also interesting to note that the groups that used the relatively least percentage of non-conventionalized expressions were the university students and the second year students at upper secondary school. The university students seem to conform to the Dreyfus brothers’ description of the rule-following behaviour of novices (using the correct terminology), while the upper secondary students mainly seem to be at a pre-novice level, where the system of rules is not yet known. However, this latter group of students tries to conform to this unknown system of rules by using the subject-specific terms, even if they in many cases fail to apply these terms correctly. We must bear in mind that the sample is very small at the university and expert level, and that no rash conclusions should be drawn from this preliminary result. More research on experts' use of communicative resources is needed. Furthermore, more research is also needed to explore the occurrence and role of non-conventionalized expressions in the learning and communication of other areas of science in which visualizations are important tools.

Implications of this study

The relationship between the intended meaning and the language used is not always straightforward, and the students' employment of correct scientific terminology does not necessarily parallel their depth of conceptual understanding. Non-conventionalized expressions usually have a specific rather than general meaning. They tend to refer to spatio-temporally related, context-bound objects or events. However, the degree of precision cannot be inferred from the non-conventionalized expressions itself, but must be inferred from the context of the utterance. We must be aware that the depth of conceptual understanding with which a term is used determines whether its meaning is precise or not.

It is difficult for a novice to go straight from a vague and general meaning of a term to a general and precise. One way of achieving this may be to start the learning process by using the term in specific contexts and showing the learners how it can be used. In the case of molecular life science, visualizations may be a way to specify abstract and general concepts. An animation, for instance, showing how a DNA chain is unspecifically *broken down* by UV radiation and specifically *cut* by a restriction enzyme might be a way to specify, and, through more experience, make the meaning of *break* and *cut* in molecular life science more precise.

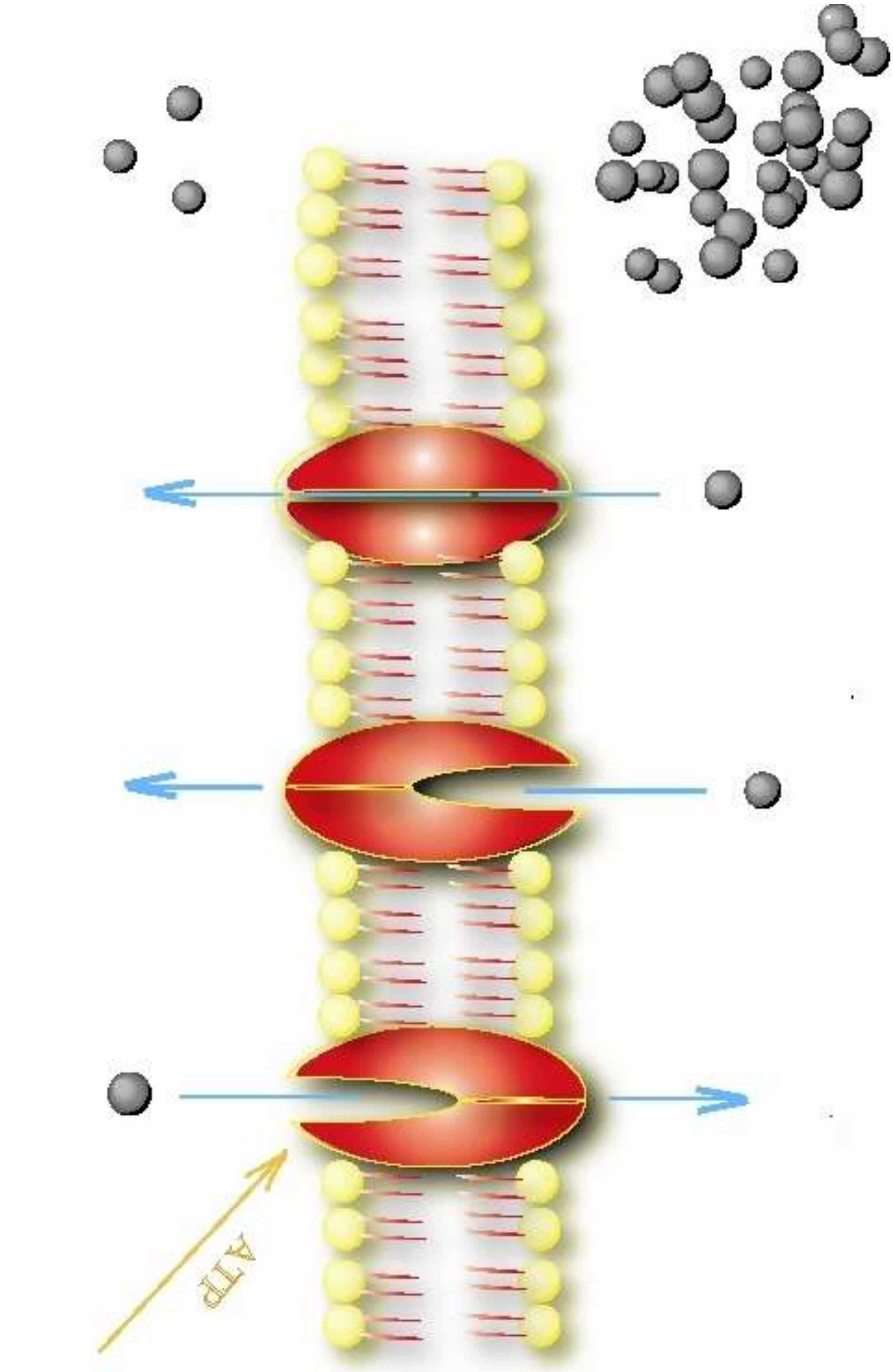
Thus, a learner might make a U-shaped turn in the model presented in Figure 1, starting in the upper left corner with an everyday, general and vague, meaning of *break* and *cut*; being given a specific example; precifying the meaning of *break* and *cut* in this specific example; and finally reaching a precise and general meaning of *break* and *cut* through becoming able to generalize the use of these terms in several different situations.

This study provides a case study of the use of expressions in the context of explaining the meaning of biomolecular visualizations. The sample is small, especially at university and expert levels. However, we find the students' and experts' use of non-conventionalized expressions in this context intriguing enough to warrant further exploration. The main result indicated by this study is that students can express an understanding of a scientific content without using appropriate scientific terminology. The students' non-scientific expressions can actually reveal more about their conceptions than a "correct" use of terminology. In many cases, the latter may actually hide rote learning and alternative thinking. Awareness among teachers of the role of non-conventionalized expressions in science classrooms may create more opportunities to discuss together with the students the precise meaning of scientific terms and how the terms should be used. The results of our study point to the inadequacy of grading students solely on the basis of their ability to use proper scientific terminology.

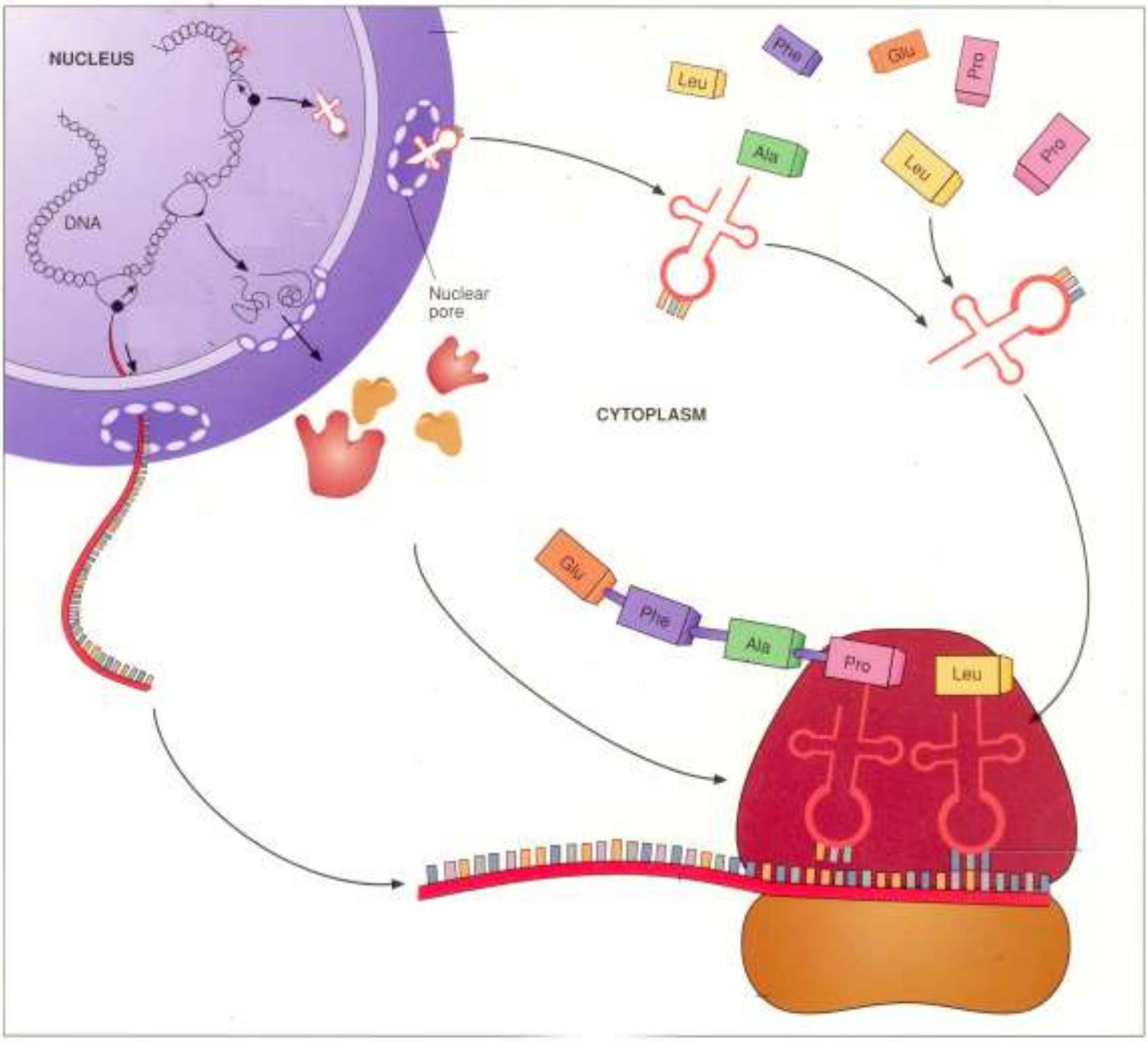
Acknowledgements

We would like to thank Martin Eriksson and Mari Stadig Degerman, who have made their diploma theses in this project. They have made a valuable contribution in the collection of data. This project has been sponsored by The Municipality of Norrköping, The Swedish Science Council (grant 2003-4275) and The Swedish National Graduate School in Science and Technology Education Research (FONTD).

Appendix I: The visualizations



Visualization 1. Visualization of transport through the cell membrane. Designed by the first author and Martin Eriksson from various examples in text books.



Visualization 2. Visualization of the process of protein synthesis. Redesigned from an original by Mix/Farber/King.

Appendix II: The interview guide

1. Briefing phase:

   Explaining the aim of the project and the interview procedure.

2. Warming up phase:
   a) Courses taken i natural science.
   b) Scientific background in the family.
   c) Interest for science – does it come from the school, from the family or from media?

3. Main phase:
   a) Visualization of the process of protein synthesis.
   b) Visualization of transport over the cell membrane.
   c) Animation of transport through water channels in the cell membrane.

4. End phase:
   a) Learning technique – How do you use text/images/notes when studying for an examination?

5. Debriefing phase:

   Possibility to change statements and to ask questions.

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