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Challenging Students' Intuitions—the Influence of a Tangible Model of Virus Assembly on Students' Conceptual Reasoning About the Process of Self-Assembly

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Abstract A well-ordered biological complex can be formed by the random motion of its components, i.e. self-assemble. This is a concept that incorporates issues that may contradict students' everyday experiences and intuitions. In previous studies, we have shown that a tangible model of virus self-assembly, used in a group exercise, helps students to grasp the process of self-assembly and in particular the facet "random molecular collision". The present study investigates how and why the model and the group exercise facilitate students' learning of this particular facet. The data analysed consist of audio recordings of six group exercises (n=35 university students) and individual semi-structured interviews (n=5 university students). The analysis is based on constructivist perspectives of learning, a combination of conceptual change theory and learning with external representations. Qualitative analysis indicates that perceived counterintuitive aspects of the process created a cognitive conflict within learners. The tangible model used in the group exercises facilitated a conceptual change in their understanding of the process. In particular, the tangible model appeared to provide cues and possible explanations and functioned as an "eye-opener" and a "thinking tool". Lastly, the results show signs of emotions also being important elements for successful accommodation.

Keywords Cognitive conflict · Conceptual change · Counterintuitive · Prior knowledge · Self-assembly · Tangible model

Introduction

Most biological complexes form through self-assembly, a process whereby higher-order structures form spontaneously and reversibly as a result of random interactions between the self-assembling components. The self-assembly process is considered to be one of nine "big ideas" that underpin the overarching conceptual content of molecular life science (Howitt et al. 2008; Sears 2008) and has direct practical applications in nanotechnological research and development (e.g. Lindsey 1991; Whitesides et al. 1991).

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Students' learning in molecular life science requires understanding of the imperceptible world of molecular entities, which cannot be acquired from experience of the perceptual world. This is because, due to their submicroscopic scale, molecules do not behave like familiar objects. Several studies have reported that students have difficulties in understanding the particulate nature of matter (Harrison and Treagust 2002), the intrinsic motion of particles and their interaction with other particles (Novick and Nussbaum 1978). This is a major educational concern since this knowledge is crucial for understanding numerous scientific concepts, for example, properties of matter, phase changes, chemical reactions and equilibrium (Nakhleh 1992; Nakhleh et al. 2005; Novick and Nussbaum 1978; Stavy 1991). There is also evidence that students have difficulties in understanding diffusion (Friedler et al. 1987; Garvin-Doxas and Klymkowsky 2008; Odom 1995; Westbrook and Marek 1991). For example, students interpret diffusion as a directional process rather than one dependent on random interactions. These findings are highly relevant to the teaching and learning of self-assembly and associated concepts, because (like diffusion) it proceeds through random motions of molecules. Several studies have addressed students' difficulties in understanding concepts related to or involved in the self-assembly process (e.g. Banerjee 1995; Garvin-Doxas and Klymkowsky 2008; Nakhleh et al. 2005). However, there has been very little investigation of students' conceptions of the complex concept of self-assembly *per se*.

Proposed sources of such difficulties are students' intuitive ideas based on everyday experiences that they bring into the learning situation (Cousin 2006; Nussbaum and Novick 1982; Perkins 1999). Indeed, Perkins (1999) uses students' difficulties in understanding the motions of objects, which may result from misimpressions from everyday life and mistaken expectations, as examples in a discussion of "conceptually difficult knowledge". Students can find it difficult to understand that (even in the macro-world) an object will continue to move at the same rate if no force, such as friction or gravity, acts on it, as this contradicts their experiences from the world (McCloskey 1983). Since the self-assembly concept incorporates several facets of known difficulty, the process seems likely to pose conceptual challenges for learners. Furthermore, since self-assembly is a key scientific "idea", there is a clear need to elucidate the specific difficulties it poses for students and explore ways to facilitate their understanding.

Thinking about molecular processes requires the ability to envision and manipulate multi-dimensional information and to synthesize this information into working mental models that incorporate invisible and abstract ideas (Larkin 1983; Redish 1994; Gordon and Pea 1995). For this, external representations, such as models, illustrations and animations, are crucial; progress in molecular life science (for instance) is tightly connected to our ability to model abstract and complex content (Kozma et al. 2000). In a previous study, we discerned signs that self-assembly was initially perceived as counterintuitive. In that study, a tangible model was a helpful tool for students to conceptualize the dynamics of the self-assembly process, in particular the facet random molecular collisions. Indeed, previous research studies have shown that tangible models may have positive effects on learning non-perceptual scientific concepts (e.g. Harris et al. 2009). The present study aims to explain how this tangible model may facilitate students' conceptual understanding of the random molecular collision facet of self-assembly, when used in group exercises.

The Influence of Prior Experiences and Knowledge on Learning

Humans strongly depend on prior conceptual understanding and prior experiences when trying to make sense of the world. When encountering new situations and knowledge, we apply our experiences of how events, objects or situations normally occur to interpret, predict and make assumptions about novel phenomena (Glaser 1983). Prior knowledge has long been considered to be the most important factor influencing learning and student achievement (Ausubel 1968; Dochy et al. 2002; Hailikari et al. 2007). *Intuitions* are beliefs that come quickly and spontaneously to mind (Kahneman 2003), based on one's generalizations of experiences of diverse circumstances in life. *Conceptual knowledge* refers to understanding the relationships between units of knowledge in a domain and of the principles that govern a domain (Rittle-Johnson et al. 2001). Based on a constructivist view of knowledge and learning, both types of prior knowledge have a major impact on students' learning (Driver et al. 1985; Smith et al. 1994). Both intuitions and conceptual knowledge are regarded as unarticulated generalizations from experiences that are loosely connected to other elements of knowledge, which may, or may not, be activated depending on context (Hammer and Elby 2002; Smith et al. 1994; Tirosh et al. 1998). In fact, Dochy et al. (2002) and Dochy et al. (1996) define prior knowledge as comprising "the whole of a person's knowledge"; it is both explicit and tacit in nature and has both conceptual and metacognitive components. Hence, prior knowledge is dynamic and available for students before a learning task. However, inadequate or fragmented prior knowledge may hamper rather than help learning (Dochy et al. 1999). Prior knowledge in the form of intuitions and conceptual knowledge are of particular interest in the current study.

Intuitions and Counterintuitive Aspects

Researchers have not reached an agreement on how concepts should ideally be presented to learners, but we know that human common sense notions are relevant to learning (Upal et al. 2007; Franks 2003). In correspondence with the division of prior knowledge mentioned above, Kahneman (2003) distinguishes between intuition and reasoning, which are attributed by Kahneman and Frederick (2002) as two distinct systems in the human mind. The first (intuitive) system operates automatically, requires very little or no effort and we have no voluntary control over it. Intuition builds on a person's earlier experience and deeply internalized knowledge, such as the learnt behaviour to pay attention when crossing a busy road, or acquired knowledge that has been internalized in a person's ontology. The second (reasoning) requires attention to perform effortful mental activities, solving a mathematical problem for example. This dual-system model has several implications for intuitive and counterintuitive notions. Kahneman (2003) and Kahneman and Frederick (2002) claim that our intuitions provide our logical thinking and reasoning system with suggestions, in the form of impressions, feelings and intentions. When everything goes smoothly, our reasoning accepts the suggestions arising from our intuitions. However, if our intuitions run into trouble, for example, when something violates our model of a familiar situation, reasoning is activated to help resolve the conflict (Kahneman 2003; Kahneman and Frederick 2002); when our intuitive expectations are not met, we need counterintuitive experiences to explain the discrepancy (Boyer 1994). In fact, a key basis for conceptual change is considered to be the experience of a divergence between existing and new conceptions. However, it is difficult to avoid errors arising from intuitions since our reasoning needs cues to explain the conflict between expectations and the observed discrepancy (Kahneman 2012). The consequence might be misunderstandings or alternative conceptions that do not coincide with the scientific definitions or explanations.

In more detail, conceptual change refers to the process whereby an individual's conceptions change over time. It has been addressed by various science education researchers, and several theories of conceptual change have been developed. Notably, fine-grained constructivists (e.g.

Smith et al. 1994; Tirosh et al. 1998) consider conceptual change to involve the modification of humans' intuitive generalizations into more sophisticated, united and coherent structures (Elby 2000).

Counterintuitive Aspects of Self-Assembly

In molecular self-assembly, a complex forms through random collisions of its components caused by their thermal motion. We all know, from experience, that a dropped ball will fall to the ground due to the gravitational force acting upon it. In contrast, submicroscopic particles move in all directions (in a gas or fluid) according to the laws of Brownian motion since submicroscopic entities have very small masses. Thus, forces (like gravity) that act strongly on macro objects have negligible effects on submicroscopic entities, which instead are profoundly affected by other forces (such as attractive and repulsive forces between the molecules). However, most humans are unlikely to draw accurate conclusions about the interactions between particles from the relationship between masses and gravity, using solely their intuition. Instead, we have intuitive expectations about how balls should behave, derived from past experiences. Thus, when trying to understand new situations and new knowledge, certain aspects activate existing mental structures (Glaser 1983).

In addition to the movements of submicroscopic particles differing from those of macro objects, their interactions, which can result in the formation of an ordered biological structure, have no parallels in the macro world. People tend to consider randomness to be the opposite of order and to assume that some kind of agent or "seed" is needed to initiate pattern formation, an intuition that arises from our everyday life (Resnick 1996). For example, if a ball is moving, we are likely to assume that it has been recently thrown, kicked or struck by a tennis racket or similar object wielded by some agent who caused the observed behaviour of the ball. More generally, humans tend to explain phenomena on the basis of central control or deterministic causality (Resnick and Wilensky 1993; Wilensky and Resnick 1999). Furthermore, this seems to impose resistance to explanations that rest on ideas of self-organization, stochasticity and decentralized processes (Feltovich et al. 1989; Resnick 1994, 1996; Wilensky and Resnick 1999). These findings suggest that students may well partake in a counterintuitive experience when confronted with the process of self-assembly, while experts see the process as self-evident.

Tangible Models and Learning

Models are simulations of some aspects of reality, and during the last decade, numerous kinds of models have been developed using diverse media (for example, animations, tangible models and interactive displays). Furthermore, due to their perceived utility, their use in teaching and learning has similarly increased recently (although the benefits of using tangible objects were proposed long ago, e.g. Montessori 1912). In research concerned with biomolecular topics, there is evidence that tangible models have positive effects on learning (e.g. Harris et al. 2009; Roberts et al. 2005; Rotbain et al. 2006). Both Harris et al. (2009) and Roberts et al. (2005) found that students perceived tangible models to be the most helpful tools for learning about protein structure and function. Harris et al. (2009) also concluded that use of a tangible model promoted students' higher-level thinking.

Discussions of an exploratory nature combined with hands-on practical activities also seem to have positive effects on learners' cognitive development (Webb and Treagust 2006), and active hands-on manipulations appear to promote the learning of complex and abstract scientific concepts (e.g. Glasson 1989; Vesilind and Jones 1996). Tangible computer user interfaces (Ishii and Ullmer 1997) have received considerable attention recently (e.g. O'Malley and Stanton Fraser 2004). Some of the proposed benefits of tangible interfaces, and tangibility more generally, are that they promote collaboration (Marshall 2007), engagement (Price et al. 2003) and learning that is more dynamic in behaviour (Zuckerman et al. 2005). However, there is still a need for more empirical-based studies examining the potential of tangible interfaces (Marshall 2007; Marshall et al. 2007).

Tangible Models of Self-Assembly

A few studies have investigated the value of models in teaching self-assembly. For example, Lego bricks that assemble in various ways (Campbell et al. 2001; Jones et al. 2006) and objects such as soda straws that assemble into complexes via capillary forces (Campbell et al. 2002) have been used to convey the principle of self-assembly. However, no models that represent biologically relevant systems or illustrate self-assembly in three dimensions have been used in any reported studies except two performed by our research group (Höst et al. 2013; Larsson et al. 2011).

In one of these previous studies (Höst et al. 2013), we identified six key facets of the process of self-assembly from the literature: *random molecular collisions*, reversibility, differential stability, influence of temperature, error correction and structural complementarity. We investigated students' conceptual understanding of these facets of self-assembly before and after interaction with an image or a tangible model. The analysis revealed that the participating students had little or no prior conceptual knowledge of the self-assembly process. Interaction with the model led to improvements in their overall scores between pre- and post-tests. Qualitative analysis of results of open-ended tasks revealed that students who interacted with the tangible model provided more multi-faceted and complex responses in the post-test than students who simply observed the image (Höst et al. 2013). Thus, the model facilitated students' development of a conceptual understanding of the dynamics of self-assembly, in particular the facet random molecular collisions.

We also found signs that self-assembly was often initially perceived to be counterintuitive and that some students tried to explain the process of self-assembly by applying "generic drivers" (often derived from prior conceptual knowledge), specifically enzymes, to the process. Prior conceptual knowledge and counterintuitiveness were therefore obvious potential sources of initial difficulties in learning about the self-assembly process.

Aims and Research Questions

The aim of the present study is to elucidate factors that are important for the previously observed (Höst et al. 2013) improvement in students' understanding of the random molecular collisions facet of self-assembly following interaction with the tangible model of the poliovirus capsid. The analysed data consist of transcribed group exercises and interviews. The specific questions we address are the following:

1. In what way do students use their prior knowledge to explain the self-assembly process?
2. In what way do the students experience aspects of the process of self-assembly as counterintuitive?
3. How does the tangible model embedded in the group exercise affect students' conceptions of the possibly counterintuitive aspects of self-assembly?

Methodology

Study design

The empirical data analysed in this research paper were originally collected as part of two studies (Höst et al. 2013; Larsson et al. 2011), in which students interacted with a tangible model in group exercises. Both studies included pre- and post-tests and a group exercise. However, the latter was arranged as a teaching-learning sequence (TLS; Méheut and Psillos 2004) and also included delayed interviews with five of the students. The group exercise in the latter study was performed early in the study and hence other elements of the TLS should not have interfered with this data. The learning effect (from pre- to post-tests) has been reported previously. In order to gain a sense of how learners construct their understanding of the self-assembly process, the analysis in this paper focuses on the interaction and communication that occurred between students during the group exercise and students' responses in the interviews; thus, language was used as a proxy for thought processes.

Tangible Model of Self-Assembly

The tangible model (see Fig. 1), which represents the self-assembly process of a poliovirus capsid, was developed by the Molecular Graphics Laboratory at the Scripps Research Institute, San Diego (Olson et al. 2007). The model is interactive and readily shows the dynamics of the process and how components attach to (and detach from) each other over time. The model consists of 12 identically shaped subunits with magnets positioned along the edges, allowing the subunits to attach to each other and form a complete capsid. All subunits in the models used in these studies are identical, but are given one of two colours, green or yellow, to emphasize the random aspect of the process. The self-assembly process is achieved by allowing students to shake the container by hand. The students were asked to observe the process and the behaviour of the subunits. The assembly process is typically completed in between 1 and 5 min.

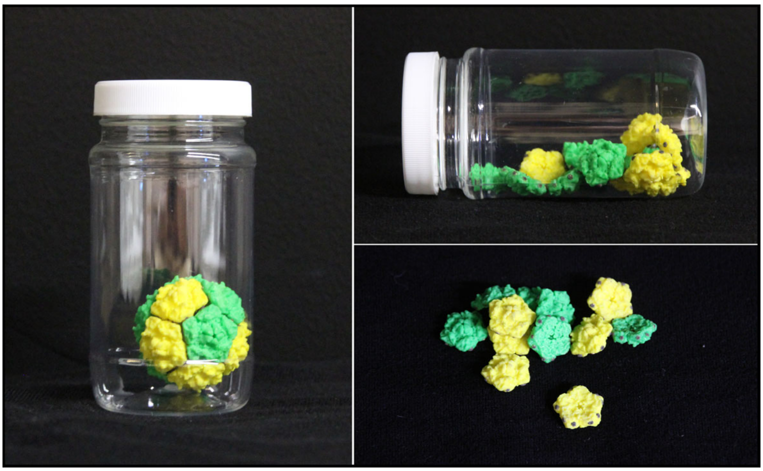

Fig. 1 The tangible model developed by Olson et al. (2007), representing the assembly of a poliovirus capsid

Sample and Data Collection

The samples consisted of 35 university students (23 females and 12 males) in total: 15 Swedish university students studying for degrees in either engineering biology or chemical engineering and 20 South African university students who were registered on a protein structure and function course. Both groups had previously passed introductory biochemistry modules covering comparable content and using similar textbooks. Hence, students' prior conceptual knowledge could be expected to be relatively similar. For the group exercises, participants were randomly organized in groups of four–seven students; the difference in number of participants in each group was an effect of the fact that students could attend different group sessions.

The process of self-assembly of virus capsids was briefly introduced before each group exercise in order to familiarize the students with its context. The exercises were structured with the aid of a written guide including instructions and questions (see Appendix 1). The discussion guidelines contained requests and questions related to the six facets of self-assembly that had been previously identified by our research group (see above). One example of a request was, "Break up the capsid and place the subunits in the container, and then close the container. Now try to assemble the subunits into a complete virus capsid." This particular request was followed by four questions, for example: "Do the subunits attach to the growing capsid in the same order each time it assembles?" Several of the questions touched upon the random motion of components (for a complete list of questions see Appendix 1). To stimulate and focus the discussions, the students were asked to try to agree upon a common answer to each question. In four of the groups, all students except one participated actively, and in two of the groups, all students except two participated actively. The discussions were generally lively and lasted on average for 30 min (Sweden) and 90 min (South Africa) and with a similar conversation intensity; 250–300 inputs/30 min.

As mentioned above, five of the students were interviewed individually approximately 10 days after the practical group exercise in one of the studies (Larsson et al. 2011). The interviews, which lasted 30–50 min, were semi-structured and carried out by a researcher using an interview protocol (Appendix 2). The dialogue focused on the facets of self-assembly and the students' attitudes towards the model and group exercise. Both the practical group exercises and interviews were audio recorded and transcribed verbatim.

The study included students from two different countries, with different cultural environments. This could have influenced the results. However, since care was taken to make sure that all students had similar educational backgrounds and both studies were performed in comparable ways, this issue should have been satisfactorily addressed. One could also question the relatively small sample sizes, but since the study relies heavily on qualitative analysis with rich descriptive findings, the results can still be generalized through recognition of patterns (Larsson 2009).

Data Handling and Analysis

During the group exercises, students discussed all five facets of self-assembly, but in this paper, the transcripts were only analysed with respect to the facet random molecular collisions (see Table 1), which was the theme of approximately 25 % of the transcribed discussion in each exercise.

An initial step in the analysis entailed pawing, also known as eyeballing, through the transcripts several times to get a sense of the material and to search for key components and patterns (Ryan and Bernard 2003). Transcripts were then analysed using qualitative content

Table 1 The explanatory nature and description of the random molecular collisions facet of the self-assembly process (*Name deleted to maintain the integrity of the review process*)

Facet	Explanation	Description
Random molecular collisions	Self-assembly proceeds through completely random collisions between subunits	Molecules in a solution are in constant thermal (Brownian) motion, resulting in frequent collisions with surrounding molecules. As a consequence of the collisions, the direction of each molecule's movement frequently changes. Thus, molecular collisions are random events, resulting in an overall random, diffusive, pattern of movements

analysis (e.g. Graneheim and Lundman 2004). The analysis was systematic and performed in two rounds (Kreuger and Casey 2000). In round one, the transcripts were deductively analysed in order to identify sections containing prior knowledge of the self-assembly process, signs of counterintuitive experiences and any understanding of the random aspects of the process. In round two, the transcripts were inductively analysed. This analysis deepened our understanding of the findings from the deductive analysis by uncovering interesting features of students' conceptual change (for example, their interaction with the tangible model), the role of emotions during the exercises and their recall of the process. The unit of analysis ranged from one to several sentences. However, each unit was always placed in context by retaining the sentences immediately before and after the selected part. Appendix 3 exemplifies our data by giving a transcript, from a group discussion, of a section where the students discuss the random molecular collision facet of the self-assembly process.

For the analysis, a memo was constructed to use as a constant comparison tool, to avoid code drifting and keep the "codes" reliable throughout the analysis (Gibbs 2007). We also used a code cross-checking method to check the quality of our results, to "minimize researcher's bias and get a measure of the reliability of coding" (Gibbs 2007 p. 99–100). This was done as follows. All of the transcripts from the group exercises and interviews were examined by two analysts. The analysts mostly concurred with respect to their findings, and in the few cases of discrepancy, they discussed the issues and reached agreement. Finally, the analysis was reviewed and discussed by a larger group of researchers, with backgrounds in molecular life sciences, protein chemistry, biochemistry, visual learning and communication, educational sciences and media technology. This also assisted in attempts to obtain rich descriptive findings, as qualitative data can be generalized through recognition of patterns, but this is dependent on the analysts' ability to recognize patterns in data that can assist interpretations of other situations, processes or phenomena (Larsson 2009).

Results

The deductive analysis searched for sections containing students' prior knowledge of the self-assembly process, signs of counterintuitive experiences and their understanding of the random aspects of the process. The findings are presented in the first three sections of the results.

Students' Use of Prior Conceptual Knowledge

Students possessed a body of relevant prior conceptual knowledge (concepts from the domain) that they tried to apply to explain the self-assembly process (see Table 2, p. 11). Examples

Table 2 Observation of specified categories in the transcripts of each group-exercise

	Group 1 (SE)	Group 2 (SE)	Group 3 (SE)	Group 4 (ZA)	Group 5 (ZA)	Group 6 (ZA)
Prior domain knowledge used in reasoning (often leading to incorrect conclusions)	x	x	x	x	–	x
Observed cognitive conflict	x	x	x	x	x	x
Acceptance of the cognitive conflict and accommodation of a new conception	x	x	x; however, alternative explanations are also considered	x	x	–
The model works as an "eye-opener"	x	x	x	x	x	–
Student used the model to test a hypothesis or explain observations/convince peers	x	x	x	x	x	x
Enthusiasm/emotions shown in connection to						
a. the model	x	x	x	x	–	x
b. an "aha moment"	x	x	–	x	–	–
Group agree upon an explanation for the virus assembly	x	x	x	x	x	–

Groups of Swedish students are indicated by "SE", while groups of South African students are indicated by "ZA"

include forces, bonds, chemical environment, molecular structure and the biological context and life cycle of the virus. However, they often used irrelevant domain knowledge, for example, involvement of receptors.

Quote 1 (group 2)

S2: I don't know, maybe they attract each other? With the magnets?
S1: Mmm…
S5: Yes, exactly, I thought about that…
S3: … receptors… things…
S5: Yes, yes, exactly… (S1: Mmm) (S4: Mmm) receptors.

Or they tried to apply relevant domain knowledge in attempts to explain the process, but draw incomplete or incorrect conclusions, as illustrated by the following excerpts.

Quote 2 (group 6)

S3: I don't understand… How does it assemble? I think we should also talk about the forces, the van der Waals forces.
S2: Yeah, whether it is bulky or not, whether they are hydrophobic.
S3: … I think there's water involved. Do you think we should consider the folding, the betas and all?
S1: (not clear)
S2: So how do the proteins actually come together and bind?
S1: (not clear) the secondary structures.
.../.../...
S2: So a certain part of the protein can't bind to another part? Maybe they repel each other because it can only bind to one place.

Two of the six groups proposed that enzymes catalyse the assembly of a virus capsid, as illustrated in the following quote.

Quote 3 (group 3)

S1: It feels like they have to make use of someone, some sort of enzyme so it goes relatively fast.
S2: They are standing there, prepared to be placed correctly.
.../.../...
S1: Some sort of enzyme.
.../.../...
S2: It feels like it is needed, it has to be like that because otherwise things may have gone very slow, without the enzyme.

Students' Intuitive Reactions to Their First Experiences of the Tangible Model

The students had not previously actively reflected on the virus capsid formation mechanism, as illustrated by the following excerpts, one from a group exercise and one from an interview.

Quote 4 (group 2)

S1: The capsid?
S2: I have no idea.
S3: It can't be random anyway – but I don't know at all.

Quote 5 (interview 1)

Student: I just thought it's DNA.
Interviewer: That DNA helped it or.

S: Yes, if something codes for something then it has to happen like that and it's gonna happen like that. I just took it for granted, I never really thought about how it's gonna happen anyway. DNA codes for it so I actually did not think about it.

Many students believed the process to be facilitated by certain factors. This is illustrated in the following excerpt (and can also be discerned in quotes 3, 8 and 10).

Quote 6 (group 3)

S1: It is strange how fast you forget. We read about it in microbiology.
S2: It feels that something is needed to facilitate it, but I don't know. I haven't thought about it before.

When asked to assemble the capsid, while keeping the subunits in the container, students were, at first, very doubtful that it was possible. The course of events appeared to contradict their previous experiences. This is demonstrated in the following excerpt, where the students are convinced that they cannot assemble the capsid by shaking the container.

Quote 7 (group 4).

[Students shake the container].
S5: Mmm.
S2: Ohhh.

S3: You can't. You can't.
S5: Yeah.
S2: How are you going to do that? It's already making… funny conformations.

This excerpt is a representative example of conversations at the beginning of the group exercise and indicates the students' intuitive reactions towards the model and its representations of virus assembly. This notion was also verified in the interviews where all five interviewees stated that it had not previously occurred to them that the assembly of a capsid could be dependent on collisions of components.

The Random Molecular Collisions Facet—a Cognitive Conflict

Students had either not thought about how an assembly of a virus capsid occurs or proposed that the process was facilitated by certain factors. For many students, it was difficult to imagine an assembly (order formation) event to be random. In fact, that random interactions between components give rise to a biological complex was puzzling to students, providing evidence of a cognitive conflict. The following two quotes, one from an interview and one from a group exercise, illustrate this.

Quote 8 (interview 2)

Student: … I was thinking that um, how can molecules just come in and just mix and just form a structure?
S: 'Cos you'd imagine that something as structured would actually be induced to form by um, some factors, that it's going to be held together by some factors and it was going to be formed in a certain way.
Interviewer: Yeah.
S: …to make sure that the structure comes out exactly the same every time.
I: Mmm.
S: So that's the kind of concept I kind of struggle.

Quote 9 (group 5)

S1: But my worry is that how do you know because you understand that the virus when it assembles itself it's very specific, like you said it's very specific. So how do they perfectly orientate themselves?

Students' Conceptual Change—the Role of the Tangible Model and the Group Exercise

The inductive analysis deepened our understanding of students' counterintuitive experiences and revealed more knowledge of students' conceptual change (e.g. the role of the model and the group exercise), the existence of emotions during the exercises and students' prolonged recall. In the following, we exemplify the findings from the inductive analysis.

The cognitive conflict was observed in all six groups, and four of the groups (1, 2, 4 and 5) went through a full sequence of conceptual development, starting with applying their previously acquired chemistry and biology knowledge to predict and explain the self-assembly process. Then, when the model did not behave as they expected, a cognitive conflict was observed. As the discussion proceeded, students in these four groups finally agreed that the process is governed by random molecular collisions. In the following excerpt, interviewee 3 explains the discrepancy between his/her prior knowledge and his/her current understanding.

Quote 10 (interview 3)

Student: Yeah! I thought it's guided by enzymes… I never knew it was random assembly.
Interviewer: Did you think that before this instruction?
S: I thought that there was a mechanism involved in assembling like (not clear) so that's what I thought.

In four of the five interviews, the interviewed students mentioned the cognitive conflict and the accommodation of a new conception. In the following excerpt, interviewee 5 describes a successful accommodation.

Quote 11 (interview 5)

Interviewer: Mmm. Did it occur to you before that processes like this could be random?
Student: No.
I: No.
S: I didn't think, no… actually I found it really difficult to understand the randomness of structures, the, how they formed.
I: Mmm.
S: But then it [the tangible model] helped me to understand that structures can form randomly.

During the group exercises, all groups investigated and discussed the random aspect of virus formation while interacting with the tangible model (see Table 2). The discussions concerned either the actual molecular collisions or the general phenomenon of random motion that underlie these collisions. One example is given below:

Quote 12 (group 3)

S2: I think it is those random collisions, it seems that if you look at it, how we shake it is randomly that piece that fits at that precise collision that seems to stick.

Moreover, several students clearly point out that the model clarified and helped them to visualize the process. These notions are illustrated in the excerpts presented below.

Quote 13 (group 4; students are referring to the model)

S4: … it is simple, like shape and stuff, it is easy, it must be easier for people to use so that they can visualize.
S1: Yes.
S4: And understand it more.

Quote 14 (interview 1).

Student: It was nice to actually see a 3D version of it, it was really, really nice.
Interviewer (I): Mmm.
S: And if you would have told me that, you know when asked if it would reassemble on its own?
I: Yes.
S: I would never have believed you if I hadn't seen it for real… [Laughter]… I was like, Oh that can't be.

The following quote illustrates how students used the tangible model in the group exercise when trying to conceptualize the nature of the process. The group has argued about whether the process is ordered or random and if the different colours have any specific meaning. Now, they put the virus subunits in the container and shake the container:

Quote 15 (group 5)

S2: You see it is assembling.
S5: And the colours don't have to be in order.
[S3 finishes assembling the virus, the other students applaud]
[Students disassemble the virus and then re-assemble it]
S1, S2, S3, S4 & S5: Yeah, you see, it works!
S3: Is it fine?
S5: It's fine but it doesn't look the same. You can see the colours are different now.
.../.../...
S5: OK, so do you think that this binding is random or guided?
S1, S2, & S5: It's random definitely.
S5: Why?
S2 & S5: Because the colours do not arrange the same way each time.
S2: So the colours were here to show us that it's not guided?
S2 and S5: Yeah.

Thus, the model was used to test different ideas and demonstrate new insights; in addition, the experience of seeing the capsid self-assemble appeared to contribute to students' conceptual change (accommodation of a new conception). In one interview, a female student nicely expressed the mediating roles played by the model and also emphasized the importance of discussing it together with peers during the group exercise.

Quote 16 (interview 1)

Student: I think we were able to interact with it, we actually had to break the model and put it together and we actually had to do it as a group and I think that was good.

In fact, all the interviewed students stressed that the discussion with peers was an essential factor in the creation of meaning around the model and the self-assembly process. In addition, the behaviour of the tangible model appeared to challenge the students' prior knowledge and induce a cognitive conflict in all groups participating in the studies (see Table 2).

Emotions, the Model and Students' Conceptual Change

All groups used the tangible model extensively in the group activity and made positive remarks about it, expressing enthusiasm and curiosity. We found no negative comments or reactions in any of the transcripts. The transcripts bear witness to the students' positive attitudes, their engagement with the learning process and a cheerful atmosphere. This is illustrated by the following excerpt:

Quote 17 (group 3)

The group has disassembled the virus model, placed it in the container and started to shake it.
S3: Cool.
(Laughs).
.../.../...

[Students continue to shake the model and discuss].
S1: Shake it, shake it, shake it!
S2: Perhaps it is too harsh… but it should not be (not clear) yes perhaps (not clear).
S3: You should try.
S1: (Laughs) Try! Now it is really hot.
S2: No, you should try, it works, it will be all right.
S1: But you have the right method, thus.
S1: (not clear) Nice! Now I am cheating (S2: Laughs) I must try some random here, otherwise it will be cheating (S2: Laughs) yes.

In this excerpt, the enthusiasm accompanying the "aha moment" signalling an emerging conceptual change is evident, and this was not an isolated event; it was evident in most groups (see Table 2). Below, we give another example from a discussion. We enter when students have been shaking the model and trying to explain the assembly for some time:

Quote 18 (group 4)

S3: Oh wow!
[Shaking]
S2: Twist, twist, twist! Come on, twist now.
(Shaking)
S4: OK, it is nearly there.
.../.../...
S2: So it's yes. It can, it can!
S3: Okay well guys, it looks like we're going to go and end up in the same place as the capsid.
S4: That's it
.../.../...
S2: Yeah! Awesome.
.../.../...
S2: That's so clever.
.../.../...
S1: And then do the subunits attach in the same order every time?
S4: No, it's random.
S1: Technically, it is a random process…
S4: It is a random process!

Prolonged Recall

An additional finding is that students used the tangible model to recall aspects of the process during the interviews, as illustrated by the following example.

Quote 19 (interview 2)

Student: However, it was 3D and we used it; I could see that okay, this is able because of this....
Interviewer: Yeah.
S: I saw it fall…
I: Mmm…
S: Saw it, yeah, I saw the side units when we were moving it…

I: Mmm…
S: They didn't come straight – some of them would remove…
I: Yeah.
S: And, and also about the random – that they come randomly.
I: Yeah, yeah.
S: And that the colour co-ordinations, we'd see that, uh, if we'd shake it, they'd draw randomly – sometimes the green will be out, in the out space…
I: Mmm…
S: Yeah, it helped us visualize it more and understand it more.

By making a connection between something experienced during the session and the scientific content, students could describe important characteristics of the process 2 weeks later. The student quoted in the following extract clearly refers back to the group exercise and the model while explaining the error-correction facet (for an explanation of this facet, see Höst et al. 2013). (S)he correctly concludes that the random nature of the process governs the error-correcting mechanism.

Quote 20 (interview 2)

S: I, I thought that the, the error-correction was made possible by the randomness of it 'cos I remember the model of the shape it, you know…but, if they do the binding in a certain way it will come out so I, I think; I thought that um, the randomness of the process, it's the principle that actually governs, um the error correction.

Summary of Results

All groups focused on the self-assembly process during the group exercise, and approximately 25 % of the transcripts were centred on the facet random molecular collisions; this part of the discussion was analysed in depth. An overview of the results presented in the preceding sections is provided in Table 2.

Three groups explicitly discussed the relationship between the scientific phenomena and the model. Previously acquired chemical terminology was used in all discussions. Some differences between the Swedish and South African groups could, however, be observed; the latter used more scientific vocabulary than the former, who used more everyday language.

Four of the groups (1, 2, 4 and 5) went through a full sequence of conceptual change; starting with applying their previously acquired chemistry and biology knowledge to predict and explain the self-assembly process, then experiencing a cognitive conflict and finally accommodating a new conception, i.e. that the process is governed by random molecular collisions. In these groups, the model was used to test ideas and acted as an eye-opener. Students seemed to experience the model and group discussion as inspiring, and the discussions were lively. Groups 1, 2 and 4 exhibited an "aha moment" during the discussion when they began to accommodate the new conception. Group 5 was very focused, but did not show the same enthusiasm as the other groups, and no distinct "aha moment" was detected. However, they accepted the cognitive conflict and came to an agreement upon a correct scientific explanation of the process. For group 3, no "aha moment" was observed, and some of the group members withheld alternative explanations.

Group 6 was very enthusiastic and talkative during their discussion and applied many different types of prior knowledge and interacted exuberantly with the model. However, they did not discuss the relationship between the model and the in vivo process. There are clear passages of cognitive conflict in the group discussion transcripts but no “aha moment” was observed and they never agreed on a specific explanation of the self-assembly process. One can speculate that group 6 may have developed their understanding of the process if they had been given more time.

Discussion

As described in the “Introduction”, the non-perceptual nature of molecular processes is often considered to be a prime cause of students’ reasoning difficulties in the domain. However, previous studies (Höst et al. 2013; Larsson et al. 2011) have shown that students developed their conceptual understanding of the dynamics of self-assembly, in particular the facet random molecular collisions, when using the tangible model in group discussions. In the present study, we aimed to explain this effect.

Students’ Counterintuitive Experiences

It has been established that humans depend on their prior knowledge, prior conceptual understanding and intuitions, to interpret the world and that these prior ideas influence their learning (Ausubel 1968; Dochy et al. 2002; Glaser 1983; Hailikari et al. 2007). The analysis of Höst et al. (2013) shows that the students have very limited or no prior conceptions of the self-assembly process.

In the initial discussion, generated by the question “How do you think such virus capsids assemble in reality?”, students’ suggestions often originated from their existing knowledge in related domains, which resulted in both correct and incorrect reasoning. This was reflected in their discussions, for instance when they proposed that enzymes catalyse virus capsid formation or receptors hold the subunits together. This exemplifies the fact that inadequate or fragmented prior knowledge may hinder conceptual understanding (Dochy et al. 1999). However, when the students experienced the unaided assembly of the virus capsid, through shaking the tangible model, it did not conform to their cognitive models. In fact, we see clear evidence in our data of reasoning difficulties related to the concept that higher-order structures can form spontaneously (and reversibly) as a result of random interactions between self-assembling components and that students experience these aspects of self-assembly as counterintuitive.

When students started to interact with the model, intuitive thoughts came rapidly and spontaneously to mind without conscious act or effort (Kahneman and Frederick 2002). These ideas were probably instantly triggered when students were confronted with a “new” representation of the non-perceptual molecular process of self-assembly. Intuitions provide our reasoning with beliefs that we cannot always justify (Kahneman and Frederick 2002), and both the expressions and feelings of the students, reported in the “Results” section, showed that they instinctively doubted that a capsid could form as they shook the container and components randomly collided. The initial function of the model therefore appeared to challenge students’ intuitions and initiate a cognitive conflict since subunits of the virus capsid behaved in ways that conflicted with the students’ prior experience of the perceptual world, i.e. counterintuitively, or contrary to their previous knowledge.

The Tangible Model Initiates a Cognitive Conflict

Obviously it is impossible to have any direct experience of molecular phenomena. Numerous studies have shown that students experience difficulties with understanding phenomena that involve the motion and random behaviour of objects (e.g. Friedler et al. 1987; Garvin-Doxas and Klymkowsky 2008; Novick and Nussbaum 1978; Odom 1995; Westbrook and Marek 1991) and the particulate nature of matter (Gabel and Samuel 1987; Harrison and Treagust 2002; Nakhleh et al. 2005). This is also in accordance with our data analysis, which revealed that the students who participated in our studies experienced a cognitive conflict as they interacted with the tangible model (shaking it and experiencing the random and reversible nature of the process made them acknowledge the conflict).

However, counterintuitive examples have been shown to engage students' prior knowledge by creating conflicts that challenge habitual thought patterns and common sense to promote reflection and deeper understanding (Gordon 1991; Lesser 1998). In fact, if adequately supported, cognitive conflicts have been shown to be important elements in the process of conceptual change because they help students to realize there is a conceptual problem (Berlyne 1965; Hewson and Hewson 1984; Nussbaum and Novick 1982), a divergence between existing and new conceptions. For example, Lesser (1998) promotes the appropriate use of counterintuitive examples in statistics curricula and argues that they can not only challenge students' intuitive beliefs but also act as motivational factors, engaging them to create the prerequisites for deeper understanding. These and the present study provide ample evidence that counterintuitive examples generate cognitive conflicts. This is also consistent with claims that generating cognitive conflicts is an effective pedagogic strategy (Berlyne 1965; Hewson and Hewson 1984; Nussbaum and Novick 1982) and promotes intellectual commitment in learners (McDermott 1993). The critical issue is, however, to identify adequate support for turning the conflict into a springboard for conceptual change.

Students' Conceptual Change

Nussbaum and Novick (1982) described an explicit strategy for initiating conceptual change concerning students' difficulties in learning about a particle model. The strategy has three parts: exposing preconceptions, creating a cognitive conflict and encouraging accommodation of the new concept(s). Perkins (1999) suggests that qualitative teaching approaches can be used in the first part of this strategy, i.e. to expose students' intuitive beliefs and interpretations. In the second part, counterintuitive experiences are required, since they naturally generate cognitive conflicts, and when interpreting a counterintuitive phenomenon in an active and exploratory way, students are confronted with the character of the focal phenomenon. Numerous variables, both cognitive and affective (emotional), may be important for the final phase of conceptual change and accommodation of new concepts (Duit and Treagust 2012; Pintrich and Schrauben 1992), some of which are explored in the present study.

In fact, our strategy coincides with Perkins' ideas by first confronting the students with their prior conceptions and creating a cognitive conflict, and then providing them with the experience of a guided group exercise in which they explore the phenomenon by using the tangible virus model as a focus tool. Our results show that four out of six groups successfully underwent a process of conceptual change by trying to apply previously acquired knowledge to predict and explain the self-assembly process, then experiencing a cognitive conflict and finally accommodating a new conception. In this process, we identified three factors that we consider to be of importance for the process: the model, discussion with peers and emotions that could be observed during the process of accommodation.

The Tangible Model Affects Students' Conception of the Self-Assembly Process

Tangible models have been shown to be useful tools for developing students' ability to model abstract and complex content and to encourage higher-level thinking (Harris et al. 2009;

Kozma et al. 2000). The tangible model appears to have dual functions in this study. In addition to the function of the tangible model already discussed, it performed a second function: it provided cues and possible explanations for the students' mistaken intuitions (Kahneman 2012), thereby facilitating conceptual change. By experiencing the molecular phenomenon through the model, they were helped to envision the process. There are numerous examples in the transcripts of students using the tangible model to test new hypotheses and subsequently demonstrate new insights to convince peers of their validity. Indeed, three groups explicitly discussed the relationship between the scientific phenomena and the model and which aspects could, or could not, be demonstrated. Hence, the model had two functions, first as an "eye-opener", and then as a "thinking tool". The inductive analysis showed that during the group exercises, the students anchored their explanations of the random nature of self-assembly by making references to the tangible model.

There is clear evidence of students' successful accommodation of new conceptions in our data, corroborating our claim that students' experiences of appropriate representations of molecular phenomena are important for their understanding, since direct experience of the phenomena is impossible. This finding is consistent with observations that the ability to envision and manipulate multidimensional information is beneficial when thinking about molecular processes (Larkin 1983; Resnick and Wilensky 1993; Gordon and Pea 1995); the choice of representations directly affects students' mental models (Dori and Barak 2001), and tangible models are helpful tools for learning biomolecular topics and fostering higher-level thinking (Harris et al. 2009; Roberts et al. 2005; Rotbain et al. 2006). The fact that students also recalled and could explain aspects of the self-assembly process by making connections to the tangible model may provide evidence of the importance of the experience of using and interacting with the model for students recall.

The Role of the Group Exercise for Students' Conceptions of the Self-Assembly Process

The discussion was vivid in all groups and the majority of the students in the groups participated (see "Methodology" section). Furthermore, the students came up with ideas and suggestions that were discussed, tested, rejected or accepted. All interviewed students stressed that the discussion with peers was an essential factor in the creation of meaning around the model and the self-assembly process. Thus, the embedding of the tangible model in the group exercise seemed to be significant for the students' conceptual development process.

Our observation that the students' interactions with peers aided their thinking and reasoning about the process coincides with Guzzetti et al. (1997)), who found that some students were able to change their intuitive ideas about physics concepts only after engaging in a discussion. The results are further supported by four previous findings. First, cognitive conflicts are necessary but not always sufficient for conceptual change. Second, students should be confronted with the character of a phenomenon in an active and exploratory way in order to reveal their intuitive beliefs (Perkins 1999). Third, allowing students to articulate and discuss their ideas helps them to revise their alternative, intuitive and often inaccurate understanding of scientific concepts (Alvermann et al. 1995; Guzzetti 2000). Fourth, exploratory hands-on practical activities have positive effects on students' ability to learn abstract science concepts (Glasson 1989; Vesilind and Jones 1996; Webb and Treagust 2006).

The Emotional Dimension and its Effect on Students' Learning

Advocates of the "classical" conceptual perspective, which overlooks affective variables, have found it challenging to develop successful instructional designs for facilitating learners' conceptual change. In sharp contrast, D'Mello and Graesser (2012) claim that students become confused when they experience cognitive disequilibrium (facing new, unexpected, knowledge) and that this can lead to disengagement and boredom if they cannot progress to acceptance of the new knowledge. However, Duit and Treagust (2012) hold that conceptual change is a powerful framework for instructional design, but researchers need to pay equal attention to both cognitive and affective variables.

Most of the groups in our study expressed an enthusiastic and joyful feeling during the group exercises and when they encountered the cognitive conflict induced by the model and their accommodation of a new conception. This is consistent with recent increased awareness of the importance of emotions (affective variables) for students' accommodation (Duit and Treagust 2012; Pintrich and Schrauben 1992). Nussbaum and Novick (1982) also noted that students' interest and enthusiasm were promoted by their three-phase teaching strategy (including the generation of cognitive conflicts) for conceptual change in their case studies. Hadjiachilleos et al. (2013) showed that students' (4th, 6th and 8th graders) conceptual change about floating and sinking was related to both cognitive and affective factors of cognitive conflicts.

It should also be noted that other factors might have contributed to the positive affective effects. In addition to the setting of a group discussion, the model/representation (in addition to its generation of cognitive conflict) itself may contribute positively. In fact, previous findings indicate that using tangible models promotes positive attitudes and thus is educationally beneficial (Penner et al. 1997); investigating the properties of an object reportedly increases motivation and attention (Sathian 1998); and tangible user interfaces have been shown to engage learners in playful learning and encourage them to develop reflective behaviour (Price et al. 2003). In addition, Schönborn et al. (2012) observed that groups using IR cameras were more emotionally engaged when encountering a conflict than groups who did not use the cameras, and this improved their understanding of the phenomenon of interest (heat transfer). In summary, the multimodal nature of a tangible model has, in itself, a stimulating effect by activating several senses (e.g. Minogue and Jones 2006), and the experience of testing something new may have a positive effect by simply being exciting.

Since instructional strategies for students' accommodation of scientific concepts are not always successful, we have not yet identified the optimal means for facilitating students' acceptance and understanding of these concepts. However, the positive emotions expressed by the students who participated in this study during the process of conceptual change strongly indicate that they were significant for successful accommodation of the new concepts. Moreover, the degrees to which the cognitive conflict, interaction with peers and interaction with the tangible model individually affected students' conceptual change cannot be determined from our data. However, we find support in the science education literature for our claim that affective factors as well as cognitive conflict may be important for successful learning (e.g. Berlyne 1965; D'Mello and Graesser 2012; Duit and Treagust 2012; Hadjiachilleos et al. 2013; Hewson and Hewson 1984; Nussbaum and Novick 1982; Pintrich and Schrauben 1992).

Conclusions

We have shown that the majority of the participating students experienced certain aspects of the self-assembly processes as counterintuitive. The counterintuitive aspects of the process, shown by the tangible model, did in turn naturally induce a cognitive conflict. From the analysis and discussion, we can conclude, as did Nussbaum and Novick (1982), that the tangible model and group exercise contributed to students' conceptual change (accommodation of the new conception) in several ways:

- Students became aware of the counterintuitive aspects of self-assembly through the tangible model.
- Students' intuitive expectations were challenged, and they personally felt the need for an explanation of how the process of self-assembly occurs.
- Students engaged in a fruitful discussion about different hypotheses of how self-assembly proceeds.
- Students experienced a "cognitive conflict" that enhanced their accommodation (conceptual change).

In addition, the model acted as a facilitator, or catalyst, in the group exercises by reducing the student's conceptual threshold, allowing them to accept the aspect they perceived as counterintuitive. The students' experience of the molecular process of self-assembly was clearly a key factor for their shift in conceptual understanding.

Implications for Teaching

The discussed results are clearly of importance for the teaching and learning of the molecular process of self-assembly, not least since self-assembly is considered to be one of nine big ideas that underpin the overarching conceptual content of molecular life science (Howitt et al. 2008; Sears 2008). However, we also believe that our results have general implications for teaching and learning of other science concepts that are problematic for students to understand due to their counterintuitive nature. Furthermore, we are convinced that the strategy can be applied at any level of education; from high school throughout undergraduate level.

We speculate that it is possible to use analogous strategies, as the one described in this paper, for teaching, e.g. carbon fixation in photosynthesis, diffusion of water over a biological membrane and adaptation in biological evolution. All three are phenomena that are documented as problematic for learners and could potentially be experienced as counterintuitive. The organic material required for growth of plants is often thought to come from the soil rather from carbon dioxide in the air (Driver et al. 1994 p. 60), which is not thought of as matter. Diffusion is often considered as directional rather than depending on random molecular movement, and adaptation is often thought of as intentional but is in fact dependent on variation due to random mutations (Garvin-Doxas and Klymkowsky 2008).

If we create a teaching-learning experience that includes appropriate teaching tools (activities, visualizations, models, simulations or focus questions/problems) that challenge students' intuitions and help them to understand the resulting cognitive conflict, students' successful accommodation (conceptual change) of the scientific concept can be achieved. For the examples mentioned above, the following activities, in combination with appropriate discussion questions, might be helpful: (1) measuring the added nutrients in soil (when cultivating a seed to a full grown plant) and experiencing that the added mass is very much less than the increased biomass, (2) using animations showing the random collision between water molecules in a membrane pore (aquaporin) upon diffusion and (3) using interactive simulations illustrating random variation in combination with selection over time for adaptation in biological evolution.

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Appendix 1

Discussion Guide

Consider the model of a virus capsid in the container. It consists of twelve subunits. In reality, each of the subunits is composed of five identical proteins. Thus, the complete capsid consists of 60 protein molecules.

Task 1

Remove the subunits from the container and try to assemble the subunits into a complete virus capsid by hand.

- How do you think such virus capsids assemble in reality?

Task 2

Break the capsid and place the subunits in the container, and then close the container. Now try to assemble the subunits into a complete virus capsid.

- Does each subunit always end up in the same place in the capsid?
- Do the subunits attach to the growing capsid in the same order each time it assembles?
- What makes it possible for a subunit to bind to another subunit?
- Do you think that the assembly process is random or guided? Why?

Task 3

Try to simulate an increased temperature in the container. Then try again to assemble the subunits into a complete capsid under the high-temperature condition.

Try to simulate a decreased temperature in the container. Then try again to assemble the subunits into a complete capsid under the low-temperature condition.

- How is the process of self-assembly influenced by temperature?
- Why does the process progress differently at the different temperatures?

Task 4

The formation of each bond between the subunits is reversible. Next time you assemble the subunits into a capsid, take extra notice of any cases where a subunit detaches from another subunit or a complex of subunits.

- Why do subunits detach from each other?

Task 5

Open the container and pick up the subunits. Examine the stability of a complex consisting of two subunits. Then add one more subunit and examine the stability of the three-piece complex. Finally, assemble the complete capsid and examine the stability.

- Can you feel any differences in the stability between the different complexes?
- How is the capsid stability influenced by temperature?
- What factors determine the thermodynamic stability?

Task 6

Two subunits might attach to each other in the wrong way. Put the subunits back into the container. The next time you assemble the capsid, make pauses to observe the different complexes between subunits. Take extra notice of any wrongly formed complexes.

- What happens to the wrongly formed complexes during assembly?
- How does the error correction mechanism work?

Task 7

It is important to also consider the limitations of a model. Although a model might clarify and explain certain aspects of a phenomenon, no model is a perfect reflection of reality. In relation to the physical model used here, consider the following questions:

- What other environmental factors, besides temperature, can influence the process of self-assembly in virus-production in a cell?
- What limitations or simplifications can you see in the physical model?
- What is the significance of the container dimensions?

Appendix 2

Interview Guide

Preparation

1. Welcome
2. Permission to make audio recordings – Informed consent form

Recording Starts

1. Date
2. Name
3. Use of visualizations

   a. Do you usually look at the text, the picture, or both text and picture first when learn about something?

   b. Do you usually use pictures, models etc.? If so, how?
   c. Do you find it hard or easy to understand pictures, models, animations etc?
4. Self-assembly tutorial

   a. How did you experience the group-exercise? Did you learn anything new during the discussion?
5. The concept of self-assembly

   a. Did you know anything about self-assembly before this tutorial?
   b. Did you learn anything new? What? When?
   c. Is it something in particular that you find hard/difficult to understand regarding self-assembly?
   d. Use virus capsid assembly as an example and ask the student to explain the following facets:

      i. Random molecular collisions
      ii. Reversibility
      iii. Influence of temperature
      iv. Differential stability
      v. Error correction
6. Please, comment your answer on statement 8.
7. Individual questions

Finishing

1. Turn of recording equipment
2. Thank you!
3. Questions?

Appendix 3

Transcript from Group Discussion

A transcript retrieved from a group discussion that shows a section where students discuss the random molecular collision facet of the self-assembly process.

Group 3

The group has disassembled the tangible virus model and placed it in the container and then started to shake it.
S3: Cool!
S4: (Laughs)
S1: (Laughs)
Discussion facilitator: … but you can start thinking about how, then I said they are gathered together and assemble but how does that happen in the cell? Do you have any idea?
S1: It feels like they have to make use of someone, some sort of enzyme so it goes relatively fast… (M2: mm)

S2: They are standing there, prepared to (M1: mm, yes) be placed correctly…
S1: We read a little about that, in microbiology but there it was more about the strands of DNA and RNA, and such (not clear)
S2: (not clear)
S1: Some sort of enzyme.
Discussion facilitator: Some sort of enzyme (KX: mm) do you agree on that everyone?
S5: Yes
S1: ((Laughter))
S6: ((Laughter)) yes
S2: It feels like it is needed, then it should be like that, because otherwise things would had been much slower than, than what they would have done without the enzyme (S?: mm) and then had some things (inaudible), anyhow in the body, not functioning as they should
Students start to shake the tangible virus model.
S1: Shake it, shake it, shake it (KX: not clear).
S2: Perhaps it is too harsh… but it should not be (not clear) yes perhaps (not clear).
S3: You should try.
S1: (Laughs) Try! Now it is really hot, yes.
S2: No, you should try, it works, it will be all right.
S1: (Laughs) But you've got the right approach, thus (S2: mm) but it was
S5: (Laughs) (not clear)
S1: (not clear) Nice! Now I am cheating (S2: Laughs) I must try some random here, otherwise it will be cheating (S2: Laughs) yes.
S5: We may not shake too hard on them (S6: no) because then they will brake again.
S6: oops, oh boy
S2: But now then, now you might get it together without it being stuck in there?
S6: Yes.
S3: Oh, one piece left (K6: Laughs)
S1: It feels like as it is like a big, big, because viruses are so small it feels, after all, that it has to be close for it to be able to go together like that and of itself (S2: yes) so it is not scattered
S2: That's true.
Discussion facilitator: Do you think that uh, that they follow a specific route or how do they assemble?
S3: (shaking the model) No! (Laughter) continue.
S2: I think it's like this, that random collisions seem, if you look at it, how we shake and keep doing it, it's random that this piece fits at that specific collision that seems to get stuck (S3: mm) (S4: mm) (S1: mm) (Discussion facilitator: mm) (S6: not clear)

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