



Students' Conceptual Sense-making of Animations and Static Visualizations of Protein Synthesis: a Sociocultural Hypothesis Explaining why Animations May Be Beneficial for Student Learning

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Published online: 04 May 2020
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Abstract

This paper analyses students' conceptual sense-making of two representations of protein synthesis: animations and static visualizations. Even though several studies have focused on the effect of animations versus static visualizations or support aspects that enable students to effectively benefit from animations, existing research has not yet analysed the activity of students' shared conceptual sense-making of these two modes of representation. Grounded in sociocultural perspectives, this study addresses this gap by investigating two classes of 10th graders working in the computer-supported Viten learning environment. One class worked on a unit containing animations, and the other on a unit where animations were replaced by static visualizations. Pre- and post-tests were administered to measure possible differences between the classes in their knowledge acquisition. Aiming to explain the quantitative findings, we performed an interaction analysis to scrutinize the interaction trajectory of two dyads, one from each condition, while working on an animation and static visualization of protein synthesis both in class and in conceptual interviews.

Our pre- and post-test findings demonstrate that students in the animated condition outperformed students in the static condition. The analysis of a dyad's interaction indicates that students' conceptual understanding develops at the juncture of segmentation of animation and text and students' collaborative conceptual sense-making. We argue that interacting with animations and static visualizations are two different interactional

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processes, and based on our theoretical grounding, we hypothesise that this difference explains the different learning outcomes in the two conditions.

By taking a sociocultural approach, the study provides a deeper understanding of the very activity in settings in which students are introduced to the scientific concepts embedded in animations versus static visualizations. Cognitive theories explaining students' learning from these two modes of representations dominate the research field. The current study contributes to the field by launching a hypothesis of why animations may be superior to static visualizations in supporting students' development of conceptual understanding in science. We introduce the collaborative link-making hypothesis, which builds on the conceptualisation of pedagogical link-making introduced by well-known researchers in the field of science education.

Keywords Animation · Static visualization · Protein synthesis · Interaction analysis · Sociocultural approach · Dynamic representation

Introduction

Learning about biological concepts and processes in the human body can be challenging since many biological processes are not tangible or visible to the naked eye (Rotbain et al. 2006; Thörne and Gericke 2014). Therefore, biology education often includes models to help students visualize micro-processes (Tregust and Tsui 2013). The adage 'a picture is worth a thousand words' refers to the powerful impact that static visualizations have in conveying complex phenomena. However, research has shown that these representations are not always perceived as intended (Pozzer-Ardenghi and Roth 2005). Representations have various meaning potentials, such that students themselves need to interpret and make sense of each given representation (Tytler et al. 2013). When a static visualization presents an invisible dynamic process (e.g. related to molecular genetics), the task of interpreting and making sense of the representation is even more demanding because students must imagine the dynamic aspect of the process. However, with computer-based technology, students can work with new modes of representation (Kress 2013). For example, in animations, the elements move on the computer screen; thus, dynamic aspects of a process may be visualized. Over the last few decades, numerous research studies have focused on the effects of animations versus static visualizations in student learning (see Berney and Bétrancourt 2016; Höffler and Leutner 2007; McElhaney et al. 2015). Grounded in cognitive theories, the majority of these effect studies can be characterized by showing positive findings in favour of animations.

By taking a sociocultural approach (Mortimer and Scott 2003; Vygotsky 1978; Wertsch 1991), the current study aims to add to the literature on students' learning from animations versus static visualizations by bringing deeper insights into the collaborative activity that occurs when students engage in a shared conceptual sense-making, specifically, here of protein synthesis. The term conceptual sense-making refers to the interpretive work that students engage in while aiming to reach for a scientific understanding of the concepts (Lemke 1990; Vygotsky 1986). In the present study, two lower secondary school classes worked on the same unit from the computer-based learning environment Viten; one class on a version containing animations, the other on a version where static visualizations replaced animations. To explore why animations may be beneficial for student learning, we performed a two-part analysis: (1) quantitative analysis of students' learning outcomes using pre-tests and post-tests and (2) qualitative analysis of students' conceptual sense-

making processes using interactional data from classes and from interviews. In the qualitative analyses, we scrutinized the interaction trajectory (Strømme and Furberg 2015) of two students—one from each class—over time while trying to make sense of the animation and the static visualization of protein synthesis. Data in the current study were collected through the Viten project¹ (Jorde et al. 2003; Mork 2006, 2011). The study aims to provide a deeper understanding of the collaborative activity and the learning potential in settings where students are introduced to scientific concepts embedded in animations versus static visualizations and thus to investigate the added value on students' learning of protein synthesis. Grounded in sociocultural perspectives on learning, the current study aims to contribute to the literature on why animations may be beneficial for student learning. The study also aims to contribute on a conceptual level by launching a new hypothesis, the collaborative link-making hypothesis, explaining the learning process when students collaborate on making sense of animations. Hence, we address the following research questions:

- How do animations compared to static visualizations improve students' understanding of gene technology?
- How do students make sense of an animation compared with a static visualization of protein synthesis?
- How can students' learning from animations versus static visualizations be explained from a sociocultural perspective?

Research on Students' Learning About Protein Synthesis

It is important for the general public to understand molecular genetics to make informed decisions on socially and ethically controversial issues related to genetically modified organisms, stem cell research, and the like. To understand genetics, one needs to be able to explain and draw connections among a large number of concepts (Lewis and Kattman 2004); hence, a number of studies have focused on the teaching and learning of genetics and inheritance and, more specifically, on students' understanding of the concepts of DNA, RNA, genes, chromosomes and proteins and of the processes of DNA replication, transcription and translation (Barak and Hussein-Farraj 2012; Thörne and Gericke 2014).

Research on students' understanding of genetics has shown that in most age categories, students' ideas centre on the rules and patterns of inheritance rather than on molecular processes (e.g. Gericke et al. 2014; Marbach-Ad 2001). Furthermore, students struggle to make links between concepts in the three organizational levels: macro (i.e. visible traits), micro (i.e. cellular phenomena) and submicro (i.e. biochemical structures, such as genes; Marbach-Ad 2001; Thörne and Gericke 2014). Several studies have shown that students generally lack an understanding of the steps between genes and traits (e.g. Lewis and Kattman 2004), and some have argued for addressing this problem by focusing on how genetic information is translated into visible traits via protein synthesis (e.g. Duncan and Reiser 2007). In response to this call, Thörne and Gericke (2014) found that teachers talked differently about both the importance and functions of proteins. Hence, students have widely differing opportunities to learn about this issue.

Several initiatives exist to better facilitate students' understanding of protein synthesis (Lewis et al. 2005), and recent studies on molecular genetics have focused on learning

¹ www.viten.no

progression (e.g. Elmesky 2013; Shea and Duncan 2013). Rotbain et al. (2006) argued for the use of models when teaching molecular genetics because genetic subcellular processes are considered difficult components to learn (e.g. Chu and Reid 2012). Studies on students' learning from animations of protein synthesis are addressed in the next section. In sum, molecular genetics seems to be a conceptually challenging topic because students have trouble linking concepts and understanding what is going on at the three organizational levels of macro, micro and submicro. Focusing more on processes related to proteins and protein synthesis may serve as a link between genes and traits.

A Review of Studies on Students' Learning from Animations and Static Visualizations

Several studies have focused on students' learning from animations. An examination of animation-oriented studies shows that most of these are effect studies investigating the differences in students' learning gains from varying conditions. These studies concerns two main areas: those investigating students' learning from animations versus static visualizations and those investigating the support aspects that enable students to effectively benefit from animations. Focusing on the first area, Höffler and Leutner (2007) and Berney and Bétrancourt (2016) conducted meta-studies, revealing animations have a substantial overall advantage. Along with studies showing the positive learning effects of animations (e.g. Ryoo and Linn 2012; Yarden and Yarden 2010), there are also examples of small or no negative effects of animations versus static visualizations (Kühl et al. 2011; Mayer et al. 2005).

Examining studies focusing on students' learning of protein synthesis, the results are even more consistent, favouring animations over static visualizations (Marbach-Ad et al. 2008; O'day 2006). Marbach-Ad et al. (2008) found that animations are more effective than both static visualizations and traditional lectures; in their study, students could watch an animation of protein synthesis either as a whole or step by step. These results were supported by O'day (2006), who also found animations superior to static visualizations. However, this was only true when the students were allowed to replay an animation several times. Furberg (2009), who conducted an interaction analysis of students' sense-making, reported that the animations stimulated student elaborations, explanations and justifications in comprehending the protein synthesis process.

Results in the reviewed studies may stem from two conditions: First, protein synthesis is dynamic in its very nature; hence, the movements in an animation capture the changes taking place over time, a feature not present in static visualizations (e.g. Marbach-Ad et al. 2008). Second, protein synthesis is a biological process that takes place on the micro level and is therefore invisible to the naked eye. Students have no everyday experience with protein synthesis, and animations enable students to visualize the dynamic aspect of the process (e.g. Yarden and Yarden 2010).

As noted by Ainsworth (2006), relatively few studies have focused on the role of animations in social learning settings. In our review, we found only three studies on animations versus static visualizations that have findings related to students' conceptual sense-making or the acquisition of scientific language. Based on interviews with teachers, Barak and Dori (2011) reported that animations can enhance students' acquisition of scientific language. Based on a combination of a qualitative analysis of students' conversations and a quantitative coding of students' utterances Yarden and Yarden (2010) found that students in both conditions gained conceptual knowledge on PCR (polymerase chain reaction); however, only the students in the animated condition could explain specific causal relationships. Contrary to these findings,

Sangin et al. (2006) found animations had no impact compared with static visualizations on either the amount or quality of students' talk when coding students' interactions.

Regarding the second area, several studies have addressed the support aspects that enable students to effectively benefit from animations (Ploetzner and Lowe 2012; Ryoo and Linn 2012). Of specific interest here are studies addressing the support aspect of the segmentation of animations (Clark and Mayer 2011; Wouters et al. 2008) since the current study focuses on segmented animation (animations presented in smaller chunks with pauses in-between). Several effect studies reports that segmentation may benefit student learning (Cheon et al. 2014), especially students with lower prior knowledge (Spanjers et al. 2011). In a review on the segmentation of animations, Spanjers et al. (2010) emphasized that these positive findings regarding segmentations may be because of the additional effect of learner control: students can decide when to continue to the next segment (Moreno 2007) and/or to repeat a segment in the animation. Based on cognitive theories, Spanjers et al. (2010) proposed two explanations for the positive findings: (1) segmentation enables students to process each element in the animation before moving on to the next and (2) the segmentation cues the students about the animation structure, displaying which segments belong together and which ones should be separated. They conclude that both explanations play a role.

Some studies on animation focusing on collaboration and/or students' language are also worth highlighting. In a study taking a dialogical approach, Karlsson (2010) scrutinized the process of a dyad producing a written account while interacting with an animation displaying a biological process. Results show that the support of animation was not a guarantee for scientific learning outcomes. Based on individual interviews Rundgren et al. (2012) reported that students could understand an animation and think 'visually' but had problems using scientific concepts while explaining the science in the animation. However, this animation was not accompanied by explanatory text. A quantitative study focusing on student learning from animation versus static visualization, found that animation was beneficial only for students working collaboratively (Rebetez et al. 2010).

A review by Ploetzner and Lowe (2012) claims that research on students' learning using animations is still in its infancy. Although numerous effect studies have been conducted (see Höffler and Leutner 2007; Ploetzner and Lowe 2012), there is a lack of studies on the very *activity* that occurs when students interact with animation. Except for Karlsson (2010), we could only find studies with a cognitive or sociocognitive orientation. As noted by Höffler and Leutner (2007), theoretical explanations for why animations may be superior to static visualizations are grounded in cognitive theories such as Schnotz's (2005) integrated model of text and picture comprehension, Mayer's (2001) theory of multimedia learning and Lowe and Boucheix's (2008) animation processing model (APM).

Although we acknowledge the significance of the studies reviewed and the cognitive theories in explaining the added value of animations, we argue for a supplementary approach providing deeper insights into learning from animations versus static visualizations. By applying a socio-cultural approach, the current study focuses on the collaborative activity in which animations and static visualizations are used as resources in students' conceptual sense-making. Focusing on the collaborative activity itself, we aim to provide a deeper understanding of learning potential in settings where students are introduced to scientific concepts embedded in animations versus static visualizations. Grounded in the sociocultural approach, the current study also aims at contributing to the body of theoretical explanations on why animations may be beneficial for student learning. Before introducing the research design, we will provide a brief account of the implications of using a sociocultural approach for students' conceptual sense-making.

A Sociocultural Perspective on Students' Conceptual Sense-Making of Animations and Static Visualizations

In a sociocultural approach, learning is seen as a social meaning-making process among students, teachers and the resources at hand (Mortimer and Scott 2003; Vygotsky 1978; Wertsch 1991). Through interaction and collaboration, students try to interpret and make sense of situations, actions, and scientific concepts. Thus, in school, language is an important tool for collaborative sense-making, and it mediates students' thinking and reasoning (Vygotsky 1986). Talk and discourse are therefore conceived of as a "social mode of thinking" (Mercer 2004).

In science education, animations and static visualizations are developed to display complex or abstract scientific concepts and processes. They are designed by experts in the field and come with clear meaning potentials (Linell 1998). The meanings of the representations are not necessarily obvious to students because understanding a representation occurs as a process. At first, students may only understand fragments of the representation, or they may even misinterpret its intended meaning. However, through continuous interactions with the representation in collaboration with peers, and supported by teachers and other resources such as written text, students may develop a scientific understanding of the representation's meaning. Thus, from a sociocultural perspective, the attempt to understand students' learning from animations and static visualizations should focus on students' conceptual sense-making (Furberg et al. 2013; Lemke 1990; Vygotsky 1986) of the representations. The term 'conceptual sense-making' has been used by Furberg et al. (2013) in their study on students' reasoning of representations in science. They pointed out that 'directing the analytical attention towards students' conceptual sense-making means that the primary focus is on the interpretive work that needs to be undertaken to make sense of the scientific concept' (p.4). The term 'conceptual sense-making', as opposed to 'sense-making', is chosen to emphasize the focus on students' work with science concepts.

In a sociocultural approach, a fundamental assumption is that students' conceptual sense-making is mediated by cultural artefacts, such as animations and static visualizations (Furberg et al. 2013; Vygotsky 1978; Wertsch 1991). Hence, the design of a representation impacts students' conceptual sense-making, implying that different types of representations may have different impacts on students' conceptual sense-making. Animations and static visualizations may therefore stimulate students' conceptual sense-making differently. Studying student learning from animations and static visualizations using this approach implies focusing on the interactions taking place between the students, and between the students and their teacher when trying to make sense of the representations. In contrast, the primary focus of most effect studies within this domain is on cognitive structures or student products.

Relevant for the current study are two aspects in a framework on pedagogical link-making developed by Scott et al. (2011) in the context of teaching and learning scientific conceptual knowledge. Pedagogical link-making is based on sociocultural perspectives on learning and occurs within the meaning-making interactions in the classroom. Building on Lemke (1990, 2000) and Vygotsky (1986), one approach in pedagogical link-making involves learning how to link scientific concepts together in thematic patterns, and another approach involves learning how to make links between different modalities of representations. Thus, based on the pedagogical link-making framework (Scott et al. 2011), the current study conceptualizes these two approaches of pedagogical link-making as conceptual link-making and multimodal link-making.

Based on the theoretical premises outlined here, we explore the collaborative activities in which animations and static visualizations are used as resources in students' conceptual sense-making. The current study aims to investigate the added value of animations versus static visualizations.

Thus, grounded in sociocultural perspectives on learning, the study also aims to contribute to the body of theoretical explanations on why animations may be beneficial for student learning.

Research Design

The current study focuses on students' conceptual sense-making processes; these are investigated in a classroom setting and in a conceptual interview between individual students and a researcher. In addition, our study also investigates students' learning outcomes, as measured by pre- and post-tests of students' conceptual knowledge before and after working with a digital unit in class. This comparative research design allowed us to investigate students' emerging understanding of protein synthesis over time and how students make sense of an animation compared with a static visualization.

Participants and Student Activities

The participants were 53 tenth grade students from two general science classes in a Norwegian lower-secondary school. The same teacher taught both classes. All students worked in pairs with the Viten gene technology unit for nine 45-min lessons over a 2-week period. Most of the lessons were conducted with the students sitting together in pairs in front of a computer; however, the last two lessons involved role-playing activities with genetically modified food. The topics of cell biology and gene technology were new to the students; thus, the students could be described as novices.

The Two Versions of the Viten Gene Technology Unit

The Viten gene technology unit constitute one of several units developed for use in lower- and upper-secondary science classes. These research-based units consist of texts, animations, simulations, interactive tasks and open-ended questions and are widely used in Norwegian schools. The learning goals of the units are linked to the National Science Curriculum.

Two versions of the Viten gene technology unit were used. The experimental class ($n = 27$) used a version involving animations, and the control class ($n = 24$) used a version involving static visualizations. The static visualizations were created from screenshots of the animations. Beyond the various representations of the scientific models, the remaining scientific content (i.e. the text including figures/graphs/pictures and tasks) was the same in the two versions of the Viten gene technology unit.

There were four animations of scientific models in the experimental unit, all of which were replaced by static visualizations in the control unit. All the animations and static visualizations could be characterized as multimodal representations (Ainsworth 2006) because they consisted of both an image and explanatory text. The representations were models of (1) the structure of the cell, (2) the structure of DNA, (3) mitosis and (4) protein synthesis. Because the qualitative part of the current study focused on protein synthesis, screenshots of the animations and of the static visualization are provided. The other three models are described in [Appendix 2](#). The visualization of protein synthesis was designed to help students reach the following learning goals: the students should be able to explain how proteins are produced in the cells by referring to (a) how and where RNA is produced; (b) how RNA is transferred to a ribosome; and (c) how the amino acids in the cytoplasm are linked to each other using the RNA recipe to

Proteinsyntese

Vi skal nå gå igjennom hvordan proteinene dannes i cellene. Denne prosessen kan deles inn i tre trinn:

- 1 Det lages en kopi av et gen fra DNA-molekylet i cellekjernen. Denne kopien kalles **RNA**.
- 2 RNA går fra cellekjernen og ut i cytoplasmaet, hvor den fester seg til et ribosom.
- 3 Aminosyrene i cytoplasmaet kobler seg sammen etter oppskriften på RNA og danner et protein.

På de neste sidene skal vi gå igjennom disse punktene mer grundig.



Fig. 1 Introduction page: overview of protein synthesis in three steps. Same page in both units

produce a protein. The introduction page of the protein synthesis lesson was exactly the same in both the experimental unit and the control unit, consisting of text that explained protein synthesis in three steps (see Fig. 1).

The introduction page was followed by three more web pages in both conditions. Figure 2 displays screenshots of the three static web pages in the control unit. Screenshot 1 displays copying of RNA inside the cell nucleus; screenshot 2 displays RNA leaving the nucleus and attaching itself to a ribosome; and screenshot 3 displays how amino acids become attached to one another via a ribosome and transport molecules by using the RNA as a recipe. All visualizations are accompanied by corresponding text. For more detailed information, see Table 4 in Appendix 1.

Figure 3 shows screenshots from the three animated web pages in the experimental unit. The animation differs from the static representation in displaying the movements of the elements involved in protein synthesis. The animation displayed in screenshotss 1, 2 and 3 is segmented, so the animation does not display the entire movement in one sequence; instead, it stops after a predefined period of time so that students must actively click to see the next movement in the

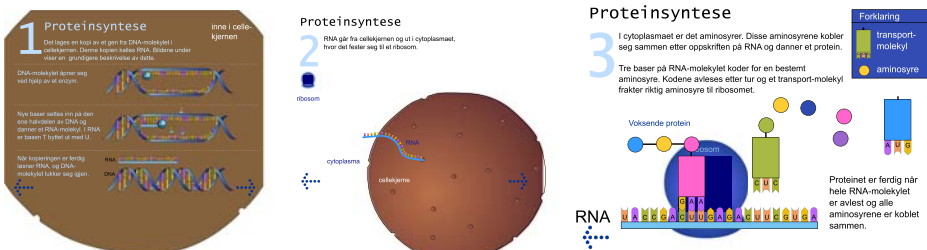


Fig. 2 Three screenshots from static representations of protein synthesis in the control unit

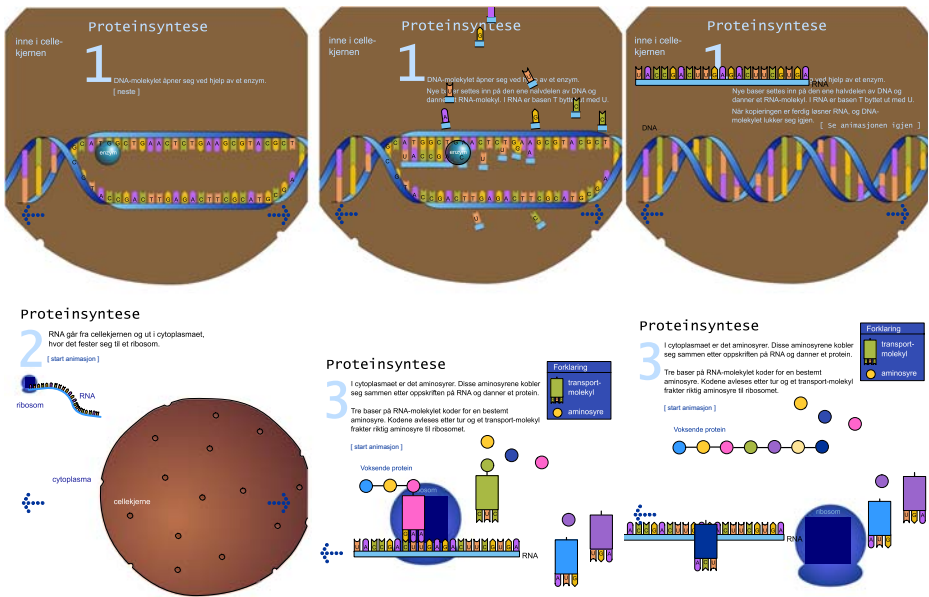


Fig. 3 Six screenshots of the animation of protein synthesis in the experimental unit

animation. The three segments of the animation display the movements in DNA and bases forming RNA, and the segments are accompanied by appearing text blocks explaining the science behind them. The animation in screenshot 4 displays a movement in RNA, and the animation in screenshots 5 and 6 display the movements in transport molecules, amino acids, ribosome and RNA to form a chain of amino acids constituting the protein.

The difference in the two interventions can be explained not only by the difference in motion in the two versions of visualizations, but also in other properties of the visualizations. The visualization of RNA formation in the control unit (screenshot 1, Fig. 2) is smaller than in the experimental unit (screenshots 1, 2 and 3, Fig. 3); thus, it can be argued that the visualization is more accessible in the experimental unit. However, it can also be argued that the visualization is more accessible in the control unit because it constitutes three snapshots of the formation of RNA on the same web page, providing an overview of the process. Finally, it should be emphasized that this study compares segmented animations to static visualizations. This implies that the pauses in the animation also should be seen as a property of the animation that may influence the results of the study. Although these pauses can be described as built-in-study-time in the experimental visualizations, both the experimental and the control class had the same time available for working with the Viten unit.

Pre-test and Post-test Data

Pre-tests and post-tests were administered to measure the differences between the experimental and control classes regarding knowledge acquisition. The tests included five items related to the animations and static visualizations, and 11 items not related to the representations. All items except one were open-ended questions. Examples of the items are listed in Table 1. The single closed question asked students to place concepts in a specific order. Each item was coded on a scale from 0 to 3, and a detailed coding scheme was developed to code the responses (see example

Table 1 Example of items in the pre- and post-tests

- 1 What are the connections among the following concepts: chromosome, DNA, base, cell nucleus and gene? (Draw a figure and explain using words)
- 2 Your body consists of thousands of cells. What do you know about the following parts in the cell: cell nucleus, ribosome, mitochondria, inner channel system, cytoplasm and cytosol and cell membrane?
- 3 Some people have a disease called diabetes. These people need insulin injections. The producers of medical drugs can now make insulin using gene technology. Do you know how insulin is created? (Draw and explain)
- 4 When you grow up, your body must create more cells, which can be used as building blocks. We call this process cell division. Can you describe how cell division takes place? (Draw and explain)
- 5 Undemeath, you can see several images^a showing how genetic information is transferred from a gene to a protein. Provide an explanation for each image

^a The images for this item consist of screenshots from the animation of protein synthesis displayed in Appendix 1. However, all text was extracted from the screenshots for use in the pre- and post-test.

Table 2 The coding scheme for the protein synthesis items in the pre-tests and post-tests

Score	Description	Sample student responses—protein synthesis item
3	Correct and detailed description of each of the images displaying protein synthesis in the test. See the appendix, Table 4. Minor mistakes are accepted	An enzyme splits the DNA. New bases come to form RNA. The DNA closes itself, and the RNA takes off. The RNA leaves the cell nucleus and out into the cytoplasm and attaches to a ribosome. The RNA is decoded by the transport molecule, creating amino acids. When the RNA is finished being decoded, a protein is created
2	Correct description of protein synthesis but no details. Contains the main points described in the introduction page—see the appendix, the first web page in Table 4. Minor mistakes are accepted	First, the DNA splits up and a ribosome comes in. One of the halves is copied and placed on the upper one. The leftover part loosens. This is called the RNA. The RNA moves to the cell nucleus. Then, the bases in the RNA are put together with the correct bases. The transport molecule carries the amino acids to the correct ribosome
1	Partially correct. Contains a correct explanation for one or two of the images displaying protein synthesis in the test	The ball is flying along [the RNA] and puts the things together. Some of the bases fly away. Specific bases fit together. When they are done, DNA is created. The ones who flew away became RNA. The RNA goes into the cell nucleus. They are put together to create some stuff
0	No answer or the answer is off-task	This is a magic ball. The magic ball attracts all the gadgets. Now the magic ball is finished. This shows a sperm trying to get into the uterus. Lots of weird stuff

in Table 2). All items in the pre-tests and post-tests were coded independently by the two authors, with a median Cohen's kappa of $d = 0.76$ [0.2–1.0], indicating a high inter-rater reliability.

Interactional Data and Analyses

To investigate why the animation group outperformed the static group on the post-test, students' interactions while working with the two versions of the Viten gene technology unit were analysed. Three student dyads from each class were videotaped during all lessons. Before the last lesson, individual conceptual interviews were conducted with the students from the video-recorded dyads,

targeting students' understanding of central concepts related to molecular genetics, such as protein synthesis. The conversations took place in front of the computer and were designed to determine students' understanding of protein synthesis. Hence, the researcher conducting the interviews tried to elicit and prompt students' ideas about protein synthesis while encouraging students to interact with the animation and static visualizations. All interviews were conducted by the first author. Field notes were used during classroom observations.

We employed interaction analysis to examine students' interactions in class (Jordan and Henderson 1995) in which talk and interaction between interlocutors are analysed sequentially. Each utterance in a selected sequence is understood and seen in relation to the previous utterance in the ongoing interaction. In our analysis, we focused primarily on the content as the conversation unfolded rather than on the linguistic work done by the students. Hence, the analysis is oriented towards the students' interactional achievements (Linell 1998). We distinguish between procedural and conceptual utterances. Specifically, procedural utterances are related to solving a task without focusing on scientific concepts (e.g. 'Are you finished reading?'). Conceptual utterances occur when a student is trying to understand the conceptual issue at stake (e.g. 'What is RNA?'). We also employed interaction analysis to examine the individual interviews; however, due to limitations in the length of this manuscript, the interviews are reported on as thick description. In the current study, we follow the interaction trajectory of two dyads (Camilla and Marianne, and Eline and Linn) and enter their interaction trajectories when they are making sense of the representation of protein synthesis in the Viten unit. Further, we follow the students into individual interviews, where they were exposed to the same representation (animation/static visualization) which they had been working with in class.

The reason for exploring the interaction trajectories of the two dyads stems from our interest in studying the students' collaborative conceptual sense-making of animations versus static visualization over time. Hence, to provide a thorough and detailed interaction analysis of these types of processes, we narrowed the focus down to two dyads, choosing to employ a dual focus on the two conditions. According to the interviews ($n = 12$), students in the static condition found it extremely difficult to explain the protein synthesis despite having worked with the topic in class. Therefore we decided to select one dyad from each of the two conditions that would fill the criteria of being high performing students (information given by teacher), as these students would have the highest potential of understanding the science of protein synthesis as displayed in the Viten unit. Selecting high performing students also helped ensure that the students were likely to be able to articulate their understanding.

Four interaction excerpts are selected from the dyads' interaction trajectories and analysed in detail (see Fig. 4). According to our research focus, we only chose excerpts from when the students were making sense of protein synthesis.

In setting A, the students try to make sense of the representation of protein synthesis, and in setting B, the students work on solving a task related to protein synthesis. Each trajectory ends with a thick description (setting C) from the individual interviews. By analysing the chronological extracts of the students' interaction trajectories, we are able to show the evolving process of students' understanding of protein synthesis. The notion of interaction trajectory refers to the analysis of interaction over time (Strømme and Furberg 2015). Scrutinizing the interaction trajectory allows us to investigate the changes that take place in students' conceptual sense-making of protein synthesis. In addition, the ethnographic information documented in the video recordings and field notes is used as a background resource for describing the educational setting. In the discussion and conclusion, the generalization is based on the larger corpus of data, an analysis of the extracts, our theoretical grounding and the literature review.

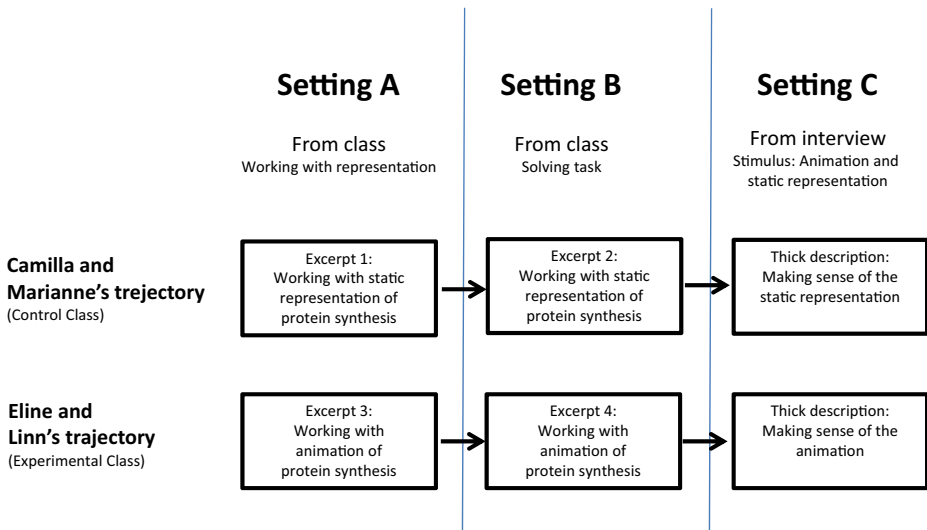


Fig. 4 The settings from which the excerpts and thick description are taken

Results

Pre- and Post-test Results

To investigate potential differences between students' performance on the pre- and post-tests and between students' performance in the two conditions, we calculated the effect sizes of the differences of means as measured by Cohen's *d* (Cohen 1992), and we performed *t*-tests. See Table 3.

Prior to using the Viten gene technology unit, there was a small difference between the students in the control class (static visualizations) and in the experimental class (animations) for the pre-test scores ($d = 0.19$; see Table 3), however, this difference is not significant ($t(49) = 0.65, p = 0.52$). Students in both conditions demonstrated a large improvement from the pre-test to post-test (animated condition: $d = 1.6$; static condition: $d = 1.34$), showing that they learned from both animations and static visualizations (see Table 3). However, the difference between the two conditions regarding the post-test scores is large ($d = 0.65$), and also significant ($t(49) = 2.27, p = 0.03$), indicating that animations are superior to static visualizations in this case.

The Students' Interaction Trajectories

Before presenting analysis of four interaction excerpts from the students' classes, and thick descriptions of individual interviews, we provide the results from the individual interview for all 12 students interviewed. For the animated condition, all six students could explain protein

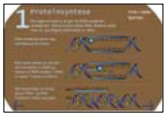
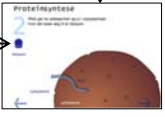

Table 3 Pre-test and post-test means and standard deviations for the two conditions

Condition	<i>N</i>	<i>M</i> (pre)	<i>SD</i> (pre)	<i>M</i> (post)	<i>SD</i> (post)
Animation	27	4.93	3.52	18.22	11.45
Static visualization	24	4.33	2.88	11.96	7.68
Total	51	4.65	3.22	15.27	10.26

synthesis in the interview while interacting with the animation. From the static condition, however, only one of the six students could explain protein synthesis to the researcher while interacting with the static visualization. Focusing on the interaction trajectories, we follow Camilla and Marianne from the control class as they work on the static visualization of the protein synthesis. Thereafter, we follow Eline and Linn from the experimental class as they work on the animation of the protein synthesis.

Camilla and Marianne’s Interaction Trajectory (Control Class)

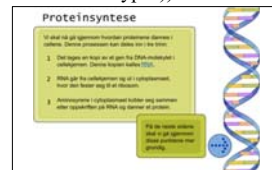
Excerpt 1: Camilla and Marianne are working with the Viten gene technology unit. They click on the first of three pages showing the static visualization of protein synthesis (Fig. 2). Camilla is in control of the mouse. They read the first page without talking. We enter the setting as Camilla signals to Marianne that she is done reading the page.

1. Camilla:	Let me know when you are done reading (.)	
2. Marianne:	Mm. (5) Now I am done. [...]	
3. Camilla:	((Clicks to the next page (page 2) in the protein synthesis. The students stare at the screen without saying anything to each other. Camilla moves the mouse over the different parts of the static visualisation)) (15)	
4. Marianne:	What are we supposed to do here, sort of? (2) It is probably possible to click on this one. ((Points to the ribosome))	
5. Camilla:	((Tries to click on the ribosome)) [Nothing happens on the screen] (4)	
6. Marianne:	Try and see whether we have received any messages from Per [the teacher]. ((Points to the box for messages on the screen)) (2) No--	
7.	[...]	
8. Camilla:	Let’s continue. ((Clicks to page nr 3 in protein synthesis)). (15) What is R: N: A:? (14)	
9. Marianne:	Uhm: Yes. (.) But weren’t there any questions related to this? [The students navigate to the task and read the wording out loud before trying to solve the task: ‘Briefly describe how genetic information flows from a gene to a protein. Make use of the following concepts: gene, RNA, ribosome, transport molecule, amino acids and protein’.]	

The central issue that we would like to highlight from Excerpt 1 is how the students interact with one another and the computer while trying to make sense of the three web pages on static visualizations of protein synthesis. As they try to make sense of the first page, they read the text next to the representation silently, signalling to each other when they are done (line 1 and 2). Without commenting the scientific content, they move to the second page. Camilla, in charge of the mouse, tries to click on the ribosome and explicitly expresses that she expects to find interactivity (line 4). Marianne does not pick up on Camilla’s comment but rather indicates that they should look for comments from the teacher in their messenger box. Again, they do not comment the scientific content. However, after continuing to the third page and studying it for a while, mostly in silence, Marianne asks a content-related question: ‘What is RNA?’ (line 8). Camilla does not pick up on this conceptual utterance. Instead, she asks a task-oriented question: ‘Weren’t there any questions related to this?’ (line 9). Consequently, there are no further scientific reflections on the content of the third page before they focus on solving the task. To summarize, when they try to make sense of the web pages containing the static visualization of protein synthesis, students’ talk can be described primarily as a conversation with a lot of silence. Moreover, the very few utterances in the conversation can be characterized as procedural rather than conceptual.

Excerpt 2: The conversation in Excerpt 2 occurs shortly after Excerpt 1, and it is representative of how the two peers are trying to solve the task on protein synthesis. The task is as follows: ‘Briefly describe how genetic information flows from a gene to a protein. Make use of the following concepts: gene, RNA, ribosome, transport molecule, amino acids, and protein’. The students are trying to solve the task by finding sentences in the unit that answer the question. We enter the conversation as Camilla detects a sentence that she finds suitable. Note that because of technical restrictions, it is not possible to cut and paste text in the Viten learning environment.

1.	Camilla:	Should I write, and then, you can read?
2.	Marianne:	Yes ((reads from the screen)) (.) RNA goes from (6) ((Camilla is not responding)) What are you doing? (.) R: N: A:
3.	Camilla:	I wrote that: (1) R: N: A: ((types while saying out loud what she types))
4.	Marianne:	Goes (2)
5.	Camilla:	Goes
6.	Marianne:	from the cell nucleus (9)
7.	Camilla:	Yes (3)
8.	Marianne:	the cell nucleus
9.	Camilla:	Yes, I have written that. Wait ((edits the text)) (9)
10.	Marianne:	the cell nucleus (.) and out (4)
11.	Camilla:	Yes
12.	Marianne:	in (1) Cyt- c: y: t:
13.	Camilla:	Wait. c: y: t:
14.	Marianne:	Oplas
15.	Camilla:	O: (3) Yes
16.	Marianne:	plasm, pla:sm:, p: l: a: s: m:, plasm ((laughs)), comma (3) Where it attaches (10)
17.	Camilla:	Where it attaches
18.	Marianne:	ehm:: (.) to a ribosome. (7) To a ribosome (3)
19.	Camilla:	Like that?
20.	Marianne:	some: ((Camilla edits the spelling in ‘ribosome’)) [The students continue to dictate and write down their answers before moving to the next topic.]



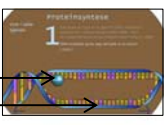
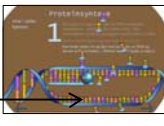
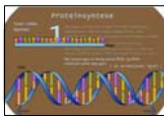
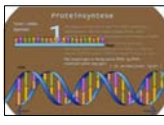
The important aspect worth highlighting from Excerpt 2 is the students’ approach to solving the task on protein synthesis. The excerpt starts with Camilla suggesting what roles the two of them should play in writing down the answer (line 1). The conversation continues with Marianne dictating small chunks of the sentence (lines 2, 4, 6, 8, 10, 12, 14, 16 and 18) and Camilla responding either by repeating parts of Marianne’s utterance (lines 5, 13, 17 and 19) or saying ‘yes’ (lines 7, 9, 11 and 15), indicating that she is finished writing and that Marianne can read a new part. Based on this, it is possible to say that the students use a strategy of transcribing text from the Viten unit to complete the task. Even though the task contains a set of new concepts, the students maintain a procedural level during their conversation.

Individual Interviews with Camilla and Marianne

As a closure to the interaction trajectory of Camilla and Marianne, we provide findings from the individual interviews when the students were exposed to the static visualization; the same representation of protein synthesis as they had been working on in class. Despite being prompted by a researcher, Camilla struggled to make sense of the static visualization and the corresponding text about protein synthesis; she was unable to explain the scientific function of RNA in protein synthesis. Marianne, however, was struggling even more to make sense of the representation and the corresponding text. She responded by complete silence, and thus, was unable to recall or talk at all about the science represented by the static visualization.

Eline and Linn's Interaction Trajectory (Experimental Class)

Excerpt 3: We enter Eline and Linn's interaction trajectory in Excerpt 3 as they are working on the Viten unit in class. They have studied the introduction page to protein synthesis. In the excerpt, they are trying to make sense of the first page of the three animated web pages of protein synthesis (see Fig. 3). On the first page, the animation is divided into three steps. For each step, corresponding chunks of text appear on the screen, adding onto the existing text. Linn is in control of the computer, and the excerpt begins with the students' initial responses to this first web page on protein synthesis.

<p>1. Linn: Okay, look now. Protein-- ((Reads from the screen)) There is a copy being made of the DNA molecule in the nucleus, and this copy is called RNA. Start the animation to get a more thorough description. Okay ((Clicks on the animation.)) (.) Enzyme. ((points to the enzyme)) (.) Here is the DNA. ((Points to the lower thread of the DNA.)) Okay. ((Reads the new text)) The DNA molecule opens up using an enzyme.</p>		<p><i>The animation shows DNA opening up by an enzyme. Simultaneously, new text appears and adds to the existing text on the screen.</i></p>
<p>((Clicks on the next step in the animation)). ((Reads the new text)) New bases are inserted. One of the halves-- Oh, my god! (2)</p>		<p><i>New text appears and adds to the existing text on the screen. The animation has not yet started. It starts by itself a few seconds after the new text appears on the screen. The animation shows that single bases fall down from the top of the screen and attach to the upper thread on the DNA.</i></p>
<p>2. Eline: ((giggles)) 3. Linn: Oh wow:: 4. Eline: Lovely (1) 5. Linn: Oh, yes, then the enzyme moves along and collects them [the bases]. Okay, let's see. ((Reads)) New bases are being placed at one of the halves of the DNA and form an RNA molecule. In RNA, the base T is replaced by U. Is it? Oh, yes, look there! ((Points with the mouse on a T-base)) (.) Cool!</p>		<p><i>The animation continues playing, showing that an enzyme moves along the upper string of the DNA to attach to the falling bases, forming the RNA.</i></p>
<p>6. Eline: We wrote that. [Refers to her written notes from the introduction page]</p>		
<p>7. Linn: Yes. ((Clicks on the next step in the animation)) Oh, my god! ((Reads the new text)) When the copying is finished, the RNA loosens and the DNA molecule closes. Oh::: that is RNA ((Surprised tone))</p>		<p><i>New text appears. The animation shows that RNA loosens and the DNA molecule closes itself.</i></p>
<p>8. Eline: But, what is RNA really?</p>		
<p>9. Linn: That is something that can start a (.) protein synthesis.</p>		
<p>10. Eline: Okay, but why do we need RNA? (.) [The conversation continues in line 11 in the subsequent excerpt (Excerpt 4).]</p>		

Two aspects from Excerpt 3 are useful to highlight. The first concerns how the animation is segmented into chunks, with corresponding segmented text influencing the students' conceptual sense-making of the animation. The excerpt starts with Linn reading the text aloud (line 1). She clicks on the animation and simultaneously turns her focus from the text to the animation before commenting on what she sees (line 1). Then, Linn clicks once more on the animation to see the next segment, and new text appears on the screen. As Linn is reading the new text aloud, bases suddenly fall down from the top of the screen (line 1); the falling bases redirect her focus from the text to animation, and she comments on the moving enzymes (line 5). When the animation stops playing, Linn turns her focus back to the text and reads aloud about the base T being replaced by the base U in the RNA (line 5). This piece of text prompts her to question whether T is also replaced by U in the animation, and she turns back to the animation to find the answer. After solving her query, she clicks on the final segment in the animation. First, she directs her focus to the animation, responding 'Oh, my god' when she sees the moving elements. She follows by redirecting her focus to the text and reading it aloud (line 7). Based on their interactions in this excerpt, it is possible to say that the segmented animation corresponds with the new segmented text, helping the students alternate their focus between the text and visualization. In addition, the pauses between the segments give the students time to check whether the information in the text corresponds to the information in the visualization.

The second aspect that we would like to address is the students' use of scientific concepts as they make sense of the animation. Looking at the different uses of scientific concepts, we see in line 1 that Linn's first comment regarding the movement in the animation refers to 'DNA' and 'enzyme.' This conceptualizing of specific elements can be seen as Linn's first step in making sense of the animation; this level of comprehension is stimulated by the students alternating their focus between the animation and text. Using scientific concepts when talking about the visualization is essential for trying to understand the phenomenon that the model is intended to represent. The next utterance containing a scientific concept is in line 5: 'Oh, yes, then the enzyme moves along and collects them'. Although this utterance contains only one scientific concept—'enzyme'—it expresses a relationship between two scientific concepts because the pronoun 'them' refers to 'bases'. Another relationship between the two concepts is expressed in lines 7 to 9, which begin with Linn exclaiming, 'Oh, that is RNA' (line 7). In response to this utterance, Eline asks the conceptual question, 'But what is RNA really?' (line 8). Linn answers by noting the concept of 'protein synthesis,' and by doing this, she states a relationship between the concept of 'RNA' and 'protein synthesis'. Hence, it is possible to describe the students' utterances as conceptual and suggest that the dynamic feature in the animation supports the students in building relationships among specific scientific concepts, which is a step towards making conceptual sense of the model representing protein synthesis.

In addition, the students' emotional expressions as they make sense of the animation should be noted. In line 1, when Linn clicks on the second step in the animation and reads another piece of text aloud, bases begin to fall down from the top of the screen (line 1). This surprises both students, and they respond by giggling and using expressions such as 'Oh, my god!', 'Oh, wow' and 'Lovely' (lines 1, 3 and 4). The students also use expressions showing excitement when they detect that the RNA is loosening from the DNA (line 7) and when they detect that the text regarding T being replaced by U also corresponds to a visualization. Hence, it is reasonable to propose that animation entails unexpected movements stimulating emotional expressions reflecting students' excitement.

Excerpt 4: In the following excerpt, the students try to solve the task on protein synthesis. The excerpt is a continuation of the previous excerpt. We enter the excerpt as Linn clicks on the task and reads the task aloud.

- | | | |
|-----|--------|---|
| 1. | Linn: | ((Reads from the screen)) Describe briefly how the genetic-- Genetic, what is that? (2) Information flows from gene to protein. Make use of the following concepts. (.)What? [<i>Surprised tone in her voice</i>] |
| 2. | Eline: | ((giggles)) |
| 3. | Linn: | We have not learned anything about that. |
| 4. | | [...] |
| 5. | Linn: | Okay. What is smart to say? (1) |
| 6. | Eline: | Well, we are to describe how information flows from a gene to a protein. Uhm:: (5) Okay, we have [<i>written</i>] that DNA transfers from the nucleus to the cytoplasm and attaches to a ribosome. ((Reads from her handwritten notebook. Linn types.)) The amino acids in the cytoplasm attach to each other using the recipe of the RNA and form a protein. This is what we have. (.) Shouldn't we look through that thing once more? (2) |
| 7. | Linn: | Yes, but look, hello, we are able to describe this. What happens (.) is that the enzyme (.) opens the DNA, (.) and then comes the--. |
| 8. | Eline: | Yes, the enzyme opens the DNA, and then the Ts are replaced by Us ((giggles)). |
| 9. | Linn: | Yes. ((writes on the computer)) |
| 10. | Eline: | Tymin by Urasil |
| 11. | Linn: | ((types while saying out loud what she types)) <Opens with the D: N: A:>. Is DNA in capital letters? <The DNA-->. [...] <Opens the DNA, and--> (2) Blibibli, what are the small ones called again? ((Points to the DNA molecule on the screen)) |
| 12. | Eline: | Uhm::: |
| 13. | Linn: | Bases |
| 14. | Eline: | The bases. The tymin bases are replaced by uracil bases. |
| 15. | Linn: | ((types while saying out loud what she types)) <And bases come and attach to the bases, which are already in the DNA.> [...] <In the DNA--> Uhm:: <they copy them. But the tymin bases become--> |
| 16. | Eline: | Replaced |
| 17. | Linn: | <Replaced with--> |
| 18. | Eline: | With urasil |
| 19. | Linn: | Urasil. <Ura: sil> Like that. Bases. ((Giggles)) Uhm:: What is happening now? [<i>They finish the task by writing about the purpose of the transport molecules before they continue to work on the next steps in the [anonymised project name] unit.</i>] |

The important aspect worth highlighting from Excerpt 4 is the students' approach towards solving the task on protein synthesis. The excerpt begins with Linn reading the task aloud (line 11). Both students are surprised by the question because they do not recall learning about this (lines 11–13). In line 16, Eline suggests that they should watch the animation once more, but Linn argues that it is not necessary (line 17). She starts describing protein synthesis by recapping that an enzyme opens the DNA (line 17). Eline agrees on the strategy and adds information about T bases being replaced by U bases (line 18). The students complete their answers by alternately providing information. This shows that, although they found the task difficult, they were able to formulate an answer in their own words, and without replaying the animation. Both students contributed by using conceptual utterances.

Individual Interviews with Eline and Linn

As a closure to the interaction trajectory of Eline and Linn, we provide findings from the individual interviews when the students were exposed to the animation; the same representation

of protein synthesis which they had been working on in class. Eline's interview showed that she was able to provide a detailed description of protein synthesis when interacting with the animation. She explained that the bases on the transport molecules must match the bases on the RNA and that the purpose of matching the bases is to ensure the correct recipe of amino acids, a scientifically correct explanation. In Linn's interview, when asked to explain protein synthesis, she remembered that DNA was copied to RNA and that in the RNA, one base was replaced by another, even though she could not remember the names of these pieces. She explained that RNA is transported out of the nucleus to the cytoplasm, where it attaches to a ribosome. She further explained that in the ribosome, amino acids are linked together to make proteins, referring to the RNA as a recipe. The goals of the Viten gene technology unit were clearly seen in both Eline's and Linn's explanations of protein synthesis.

Discussion

Regarding our first research question "How do animations compared to static visualisations improve students' understanding of gene technology?", the students in both the animated and static conditions showed considerable gains in the post-test. However, the students in the animated condition outperformed those in the static condition. These results are in line with those of several other studies showing that animations are more beneficial than static visualizations for student learning in general (Berney and Bétrancourt 2016; Höffler and Leutner 2007) and for learning about protein synthesis in particular (Marbach-Ad et al. 2008; O'day 2006). The current study extends these findings by providing deeper insight into students' learning potential and sense-making processes in settings where the students are introduced to scientific concepts by means of animations versus static visualizations.

Analysis of the two dyads' interaction trajectories indicates that animations seem to be more effective than static visualizations in supporting students' understanding of protein synthesis. This is illustrated both by focusing solely on the interaction trajectory of the dyad in the dynamic condition and by comparing the two dyads' interaction trajectories. The dyad from the static condition solved the task on protein synthesis using a strategy of transcribing text from the Viten unit, while the dyad from the animated condition solved the task by recapping information from the visualization using scientific concepts, even without replaying the animation. Students who are able to use scientific concepts in context and in relation to other concepts and to communicate these concepts to others, for example, through answering a task, reach higher levels of conceptual understanding than students who rely on a strategy of transcribing text from teaching materials when communicating their understanding (Bravo et al. 2008; Haug and Ødegaard 2014).

Results from the interviews support the findings on students' interactions in class, in favour of the hypothesis that animations are more effective than static visualizations in improving students' understanding of protein synthesis. Despite working with the static visualizations in class and preparing for the test, five of the six students in the static condition, including Camilla and Marianne, were not able to explain the process of protein synthesis in the interviews. In contrast, all six students in the animated condition, including Eline and Linn, could explain protein synthesis in the interview while interacting with the animation. Considering that the students are novices in the field,

our findings echo those of Yarden and Yarden (2010), who showed that when compared to static visualization, animation is an effective tool for students with low prior knowledge. Exploring why animations are more effective in supporting students' understanding of protein synthesis, we argue that it is necessary to focus on students' conceptual sense-making as they interact with the animation and static visualization and with each other. Our second research question "How do students make sense of an animation compared with static visualisation of protein synthesis?" targets this issue. The results from the static condition show that the students did not talk much when interacting with the static visualizations, despite the fact that they were described by their teacher to be generally talkative. Moreover, the little conversation they had was procedural conversation rather than conceptual. This begs the question of whether the difference in conceptual sense-making between the two conditions can be explained by the differences in the two multimodal representations in the two Viten units. Relatively few studies have focused on the role of animations in social learning settings (Ainsworth 2006) and, hence, on students' conceptual sense-making; these studies have disparate results, showing that animations may enhance the acquisition of scientific language (Barak and Dori 2011); stimulate students' elaborations, explanations and justifications (Furberg 2009); and enhance the conceptual status of students' talk as they interact with molecular genetic representations (Yarden and Yarden 2010). However, Sangin et al. (2006) found no difference on the quality or amount of students' talk as they interacted with the animations as compared to static visualizations.

Several studies show that students' learning outcomes are significantly increased by segmenting an animation (Moreno 2007; Spanjers et al. 2010). Based on various cognitive groundings, these studies explain that the positive findings result from pauses which create time for reflection. The current study does not claim that the findings of learning through animations being superior to static visualization are because of the dynamic aspect of the animation; rather, in this case, we suggest that the results are because of a combination of the dynamic aspect: the animation being segmented and the segmentation of the text. It is at the intersection of this dynamic aspect and of the students' collaborative sense-making that students' conceptual understanding develops. We argue that this process is different from a student interacting with a static visualization. Based on our theoretical grounding, we hypothesise that this difference explains the various learning outcomes in the two conditions. We will elaborate further on this in the next section.

The Collaborative Link-Making Hypothesis

In the following, we will address our third research question: "How can students' learning from animations versus static visualisations be explained from a sociocultural perspective?" To obtain a nuanced understanding of why animations may be superior to static visualizations in supporting students' development of scientific understanding, we will argue that it is necessary to focus on students' collaborative conceptual sense-making as they interact with the representation. Our review demonstrates the lack of studies in the field focusing on students' talk. Moreover, the results of previous research on students' learning from animations versus static visualizations have thus far been explained by cognitive theories, such as Schnotz's (2005) integrated model of text and picture comprehension, Mayer's (2001) theory of multimedia learning, or Lowe and Boucheix' (2008) animation processing model (APM). However, there

is a theoretical gap in the literature in the field of learning from animations versus static visualizations, not considering sociocultural perspectives.

Based on a sociocultural approach, we launch the collaborative link-making hypothesis, which explains why animations may be superior to static visualizations in developing students' scientific understanding. The hypothesis builds on two out of the six approaches in the framework on pedagogical link-making developed by Scott et al. (2011) in the context of teaching and learning scientific conceptual knowledge in classroom settings: 'making links between scientific concepts' and 'making links between modes of representations', which are seen as essential for students to develop their understanding in science. The current study conceptualizes these two approaches as conceptual link-making and multimodal link-making. By building on these concepts when introducing the new hypothesis on students' learning from animations, the current study brings Scott et al. (2011)'s sociocultural framework of pedagogical link-making into the field of students' learning from animations compared to static visualizations.

Our collaborative link-making hypothesis postulates that animations foster conceptual and multimodal link-making (Scott et al. 2011) that takes place within students' conceptual sense-making. Focusing on conceptual link-making, the process of making links between concepts is essential in learning conceptual scientific knowledge (Lemke 1990; Mortimer and Scott 2003; Vygotsky 1986). According to our hypothesis, this process can be supported by collaborative sense-making and interactions with an animation. When students sit together watching and interacting with an animation of a scientific process, they are likely to orally describe to each other what they see and make short conceptual utterances by naming specific elements in the animation. Hence, the collaborative aspect is fundamental in this conceptual link-making process. As an element moves, the collaborating students experience the need to express the relationship between a specific element (representing a scientific concept) and other specific elements (representing other scientific concepts). These short, conceptual utterances are immediate responses to the animation and to the utterances stated by their peers. Hence, the dynamic features of the visualization stimulate students' collaborative conceptual sense-making and support students in making links between scientific concepts.

Turning the focus to multimodal link-making, Scott et al. (2011) emphasized that supporting students in making links between the modalities of representations will enhance their understanding of scientific concepts. Similarly, Lemke (1990) argued that it is only in the integration of the different modalities of representations that the whole concept exists. Hence, learning to make links between the modalities of representation is an important aspect of schooling. According to Ainsworth (2006), the different types of representations within a multiple representation—for example, an image and text together—should not be considered in isolation; rather, they should be seen as entities that interact together. In line with our collaborative link-making hypothesis, we argue that animations should be segmented and accompanied with corresponding text explaining the science found in the moving segment. In segmented animations, the movements are presented in smaller chunks with pauses in-between. In these pauses, students alternate their focus between the text and visualization, and prompted by these two modalities, the students use scientific concepts from the text to comment on the movements in the visualization. While students are listening to each other's comments

stimulated by the two modalities, they may also comment on each other's utterances. Thus, in this process, students' development of understanding is stimulated both by the animation, the text and the collaborative conceptual sense-making. Segmented animations accompanied by text support students in alternating their focus between the two modalities, fostering multimodal link-making and thus, support conceptual understanding. According to Rundgren et al. (2012), 'student's problem may not be to understand the visualisations and to think "visually", but rather to reformulate this understanding into a subject-specific conventionalised language' (p. 908). However, the animations in their study were not accompanied by text. According to our collaborative link-making hypothesis, it is the very combination of the dynamic feature in the animation and the corresponding text that supports students in using 'subject-specific conventionalised language'.

Furthermore, the current study indicates that animations may encourage emotional engagement. Emotions in science classrooms are important for students' development of attitudes towards learning science (Maria et al. 2003). In this respect, the unexpected movements in the animation that caused excitement stimulated positive attitudes towards science and learning in science, which, in turn may have motivated students to continue focusing on and making sense of the representation.

Concluding Remarks

This study has focused on students' conceptual sense-making in a naturalistic setting as they interact with animations and static visualizations embedded in a Viten gene technology unit. The contribution of this study is threefold: First, on an empirical level, we have proposed a more nuanced understanding of how students learn when interacting with animations versus static visualizations. Second, on a design level, the current study demonstrates the value of designing segmented animations, as this feature of the animation may foster conceptual sense-making in general, as well as conceptual link-making and multimodal link-making in particular. Third, our conceptual contribution is the development of the collaborative link-making hypothesis postulating that animations foster conceptual and multimodal link-making (Scott et al. 2011) that takes place within students' conceptual sense-making. This hypothesis is grounded in sociocultural theory, and since the explanatory models on students' learning from animations versus static representations so far are based on cognitive theories, our hypothesis can be seen as new shift of lenses used to understand students' learning from these two modes of representations.

Acknowledgments This study was conducted in the context of the Viten.no project, which is housed by the Norwegian Center for Science Education. We would like to thank Wenche Erlien and Øystein Sørborg from the Viten research team, who designed the Viten units used in the current study. In particular, the authors would like to thank Prof. Doris Jorde from the Viten research team for her invaluable guidance in planning the research design, along with Prof. Sten Ludvigsen, Assoc. Prof. Anniken Furberg, Assoc. Prof. Palmyre Pierroux, Assoc. Prof. Maria Vetleseter Bøe, Sven Magne Bakken, Prof. Ella Idsøe and Prof. Tormod Idsøe for their valuable comments on this paper.

Funding Information Open Access funding provided by University of Oslo & Oslo University Hospital.

Appendix 1

Table 4 The text explaining protein synthesis in the Viten learning environment





<p>Proteinsyntese</p> <p>Vi skal nå på igjennom hvordan proteinene dannes i cellene. Denne prosessen kan deles inn i tre trinn:</p> <ol style="list-style-type: none"> 1 Det lages en kopi av et gen fra DNA-molekylet i cellekjernen. Denne kopien kalles RNA. 2 RNA går fra cellekjernen og ut i cytoplasmaet, hvor den fester seg til et ribosom. 3 Aminosyrene i cytoplasmaet kobler seg sammen etter oppskriften på RNA og danner et protein. <p>På de neste sidene skal vi gå igjennom disse punktene mer grundig.</p> 	<p>Protein synthesis</p> <p>We will now explain how proteins are created in cells. This process can be divided into three steps:</p> <ol style="list-style-type: none"> 1. In the cell nucleus, a copy of a gene from the DNA molecule is made. This copy is called RNA. 2. RNA leaves the cell nucleus to the cytoplasm, where it attaches to a ribosome. 3. The amino acids in the cytoplasm attach to each other using the RNA recipe and create a protein. <p>On the next page, we will explore these steps more thoroughly.</p> <p>RNA stands for ribonucleic acid. In contrast to DNA, RNA consists of a single thread. Moreover, RNA consists of the base uracil (U) instead of the base thymine (T).</p>
<p>Proteinsyntese</p> <p>inne i cellekjernen</p> <p>1 Det lages en kopi av et gen fra DNA-molekylet i cellekjernen. Denne kopien kalles RNA. Start animasjonen og få en grundigere beskrivelse av dette. [start animasjonen]</p> 	<p>Protein synthesis</p> <p>In the cell nucleus, a copy of a gene from the DNA molecule is made. This copy is called RNA. Start the animation to receive a more thorough description of this process. [start animation] Inside the cell nucleus</p>
<p>Proteinsyntese</p> <p>inne i cellekjernen</p> <p>1 DNA-molekylet åpner seg ved hjelp av et enzym. [neste]</p> 	<p>The DNA molecule opens up via an enzyme. [next]</p>
<p>Proteinsyntese</p> <p>inne i cellekjernen</p> <p>1 DNA-molekylet åpner seg ved hjelp av et enzym. Nye baser settes inn på den ene halvdel av DNA og danner RNA-molekyl. I RNA er basen T byttet ut med U.</p> 	<p>New bases are being placed in one of the halves of the DNA to form an RNA molecule. In RNA, the base T is replaced by U. [next]</p>

Table 4 (continued)

<p>Proteinsyntese</p> <p>1</p> <p>inne i cellekjerne</p> <p>RNA</p> <p>Når kopieringen er ferdig løser RNA, og DNA-molekylet lukker seg igjen. [Se animasjonen igjen]</p> <p>DNA</p>	<p>When the copying process is finished, the RNA loosens, and the DNA molecule closes again. [see the animation over again]</p>
<p>Proteinsyntese</p> <p>2</p> <p>RNA går fra cellekjerne og ut i cytoplasmaet, hvor det fester seg til et ribosom.</p> <p>[start animasjon]</p> <p>RNA</p> <p>ribosom</p> <p>cytoplasma</p> <p>cellekjerne</p>	<p>Protein synthesis RNA moves from the cell nucleus out to the cytoplasm, where it attaches to a ribosome. [start animation]</p>
<p>Proteinsyntese</p> <p>3</p> <p>I cytoplasmaet er det aminosyrer. Disse aminosyrene kobler seg sammen etter oppskriften på RNA og danner et protein.</p> <p>Forklaring</p> <ul style="list-style-type: none"> transport-molekyl aminosyre <p>Tre baser på RNA-molekylet koder for en bestemt aminosyre. Kodene avleses etter tur og et transport-molekyl frakter riktig aminosyre til ribosomet.</p> <p>[start animasjon]</p> <p>Voksende protein</p> <p>RNA</p>	<p>Protein synthesis In the cytoplasm, there are amino acids. These amino acids attach to one another using the RNA recipe to form a protein. Three bases of an RNA molecule establish the code for a specific amino acid. The codes are read off one by one, and a transport molecule carries the correct amino acid to the ribosome. [start animation] Growing protein</p>
<p>Proteinsyntese</p> <p>3</p> <p>I cytoplasmaet er det aminosyrer. Disse aminosyrene kobler seg sammen etter oppskriften på RNA og danner et protein.</p> <p>Forklaring</p> <ul style="list-style-type: none"> transport-molekyl aminosyre <p>Tre baser på RNA-molekylet koder for en bestemt aminosyre. Kodene avleses etter tur og et transport-molekyl frakter riktig aminosyre til ribosomet.</p> <p>[start animasjon]</p> <p>Voksende protein</p> <p>ribosom</p> <p>RNA</p>	<p>The protein is finished when the entire RNA molecule has been read and all amino acids are attached. The end.</p>

Appendix 2

Description of the animations and the static visualizations.

The representations presented as either animations or static visuals were models of (1) the structure of the cell, (2) the structure of DNA, (3) mitosis and (4) protein synthesis. Three of these models were designed as segmented animations (models 2, 3 and 4). The animation of 'the structure of the cell' displayed interactive organelles. When the students clicked on an organelle, the organelle moved out of the cell before entering a still image, and explanatory text appeared next to the organelle. In the static version of the 'structure of the cell', all text on the organelles was presented under the cell's static visual. The animation of the 'structure of DNA' displayed four static visuals with an animated zooming effect between them. When students clicked on the cell nucleus, chromosomes slowly appeared inside the cell nucleus, and the image of the cell nucleus slowly disappeared. When the students clicked on the static visual of the chromosomes, the animation zoomed in on one of them, displaying how chromosomes are built of a DNA helix coiled around proteins. In the final segment, the animation zoomed in on the DNA helix, displaying how DNA is built of nucleotides. The static version consisted of the same four static visuals used in the animated version; however, in the static version, there was no zooming effect between the still visuals. The text was presented in the same way in both versions; that is, new text appeared on the screen for each static visual. The representations of 'mitosis' and 'protein synthesis' both displayed the biological processes taking place over time. The animation of mitosis consisted of six animated segments, each displaying a different step in the division process. Between each of the animated segments, static visuals appeared, accompanied by text explaining the science in each segment of the animation. The same static visuals were also used in the static version. In this version, six visuals of a cell were placed underneath each other on one web page with arrows in-between them. The students had to scroll down the web page to see the entire visualization of mitosis. Descriptive text was placed next to each of the static visuals. The animation and static visualization of protein synthesis are described in the methods section.

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