Res Sci Educ (2010) 40:375–402
DOI 10.1007/s11165-009-9126-0

Learning Using Dynamic and Static Visualizations: Students' Comprehension, Prior Knowledge and Conceptual Status of a Biotechnological Method

Hagit Yarden · Anat Yarden

Abstract The importance of biotechnology education at the high-school level has been recognized in a number of international curriculum frameworks around the world. One of the most problematic issues in learning biotechnology has been found to be the biotechnological methods involved. Here, we examine the unique contribution of an animation of the polymerase chain reaction (PCR) in promoting conceptual learning of the biotechnological method among 12th-grade biology majors. All of the students learned about the PCR using still images (n=83) or the animation (n=90). A significant advantage to the animation treatment was identified following learning. Students' prior content knowledge was found to be an important factor for students who learned PCR using still images, serving as an obstacle to learning the PCR method in the case of low prior knowledge. Through analysing students' discourse, using the framework of the conceptual status analysis, we found that students who learned about PCR using still images faced difficulties in understanding some mechanistic aspects of the method. On the other hand, using the animation gave the students an advantage in understanding those aspects.

Keywords Animations · Biotechnology education · Conceptual status · Dynamic visualization · Prior knowledge · Static visualization

Introduction

It was recently suggested that school science should play a major role in the development of a citizenry that is capable of dealing with the scientific developments and changes in the vital field of biotechnology, and their influence on our everyday lives (Steele and Aubusson 2004). Biotechnology can be defined in the broadest sense as any technological application that uses biological systems, living organisms or derivatives thereof, to make or modify products or processes for specific use. This definition is made more specific by spearing it into activities that can be considered "traditional"; that is, bread-making, brewing wine and beer, and those involving genetic engineering, that can be considered "modern" or "new

---

H. Yarden · A. Yarden (✉)
Department of Science Teaching, Weizmann Institute of Science, Rehovot 76100, Israel
e-mail: anat.yarden@weizmann.ac.il

technologies" (France and Gilbert 2005). Over the last decade, agriculture, industry and medicine are being altered by new technologies, including gene therapy in medicine, pesticide resistant crops and genetically modified foods (Edmonston 2000). Biotechnology is also an aspect of science in which its content is rich with opportunities for applying the knowledge, understanding and attitudes gained from the study of science to everyday life (Lock et al. 1995). Indeed, the importance of biotechnology education has been recognized in a number of international curriculum frameworks around the world (Conner 2000; Solomon 2001; Steele and Aubusson 2004). The Israeli Ministry of Education has also acknowledged the relevance and importance of teaching biotechnology at the senior high-school level, for both biology and biotechnology majors (Israeli Ministry of Education 2003, 2005). Although biotechnology education has gained significant recognition, less has been published about how to teach this topic effectively.

One of the most problematic issues to comprehend while learning biotechnology is the methods involved (Falk et al. 2008). Molecular biology methods are completely unfamiliar to most students, because they are remote from their everyday experiences and the students usually have no opportunity to experience them hands-on in the school laboratory (Olsher et al. 1999; Steele and Aubusson 2004). In addition, the methods are based on the understanding of abstract concepts and molecular processes, known to be an intellectual challenge for high-school students (Falk et al. 2008; Bahar et al. 1999; Lewis and Wood-Robinson 2000; Marbach-Ad 2001). Thus, there is a strong need for a more concrete and accessible means of demonstrating and visualizing the course of action and applications of molecular processes.

Multimedia instructional environments in general, and animations in particular, have great potential for improving the way people learn (Kelly and Jones 2007; Kozma 2003; Mayer and Moreno 2002; Reiber 1991; Stith 2004; Williamson and Abraham 1995). One of the most unique advantages of animation is that in some situations, it can provide a virtual alternative to practical work. When an animation simulates real processes which include, for instance, motion, it allows learners to execute "virtual experiments" that would be costly, dangerous, or otherwise not feasible in a school laboratory. The idealization of complex laboratory experiments, as it appears in simulations, is helpful in reducing error and focusing attention on particular abstract concepts, or isolating variables that are normally combined (Hennessy et al. 2006).

Our major objective is to investigate the unique contribution of animations in facilitating students' understanding of molecular processes in the context of learning biotechnological methods. In this study, we explored the use of an animation we developed in order to promote high-school biology students' comprehension of the biotechnological method polymerase chain reaction (PCR), in the framework of learning biotechnology. Our study is based on previous work that provided the cognitive basis of learning using visualization tools (Mayer 1996; Mayer and Moreno 2002; Sweller 1994), as well as on studies that examined the use of both dynamic and static visualizations (Hoffler and Leutner 2007; Tversky and Morrison 2002). For our data analysis, we used the perspective of conceptual learning (Posner et al. 1982). We refer here to conceptual learning of biotechnological methods in terms of the acquisition and application of new knowledge resulting in concepts and symbolic representations (Maclellan 2005).

The Cognitive Basis of Learning Using Visualization Tools

The potential of animations for promoting students' understanding of diverse disciplines in science education has been discussed at length in the literature (Ardac and Akaygun 2005; Hegarty 2004; Hoffler and Leutner 2007; Tversky and Morrison 2002). By animation, we refer to a simulated motion picture depicting the movement of drawn objects. In contrast, video refers to a motion picture depicting the movement of real objects. Similarly, an illustration is a static picture of drawn objects, whereas a photograph is a static picture of real objects (Mayer and Moreno 2002).

In designing multimedia presentations involving animations, instructional designers base their decisions on theories of how students learn from words and pictures. Those theories are relevant for learning and teaching in general, and for learning and teaching science in particular. One of those theories is the Cognitive Theory of Multimedia Learning (Mayer and Moreno 2002), which is based on three fundamental assumptions: the first is the dual-channel assumption (Paivio 1986), according to which humans have separate channels for processing visual and verbal representations. Therefore, information encoded in both channels will be better remembered than information encoded in only one of the channels. Since pictures, whether they are dynamic or static, may be coded both visually and verbally, they are more likely to be remembered than words. According to Hoffler and Leutner's (2007) meta-analysis, there is strong empirical evidence that learning outcomes are improved by presenting the learner with verbal and pictorial information in a coordinated fashion. Predominantly in science education, when we are dealing with phenomena that are mostly abstract, the integration between verbal and concrete pictorial information seems to be most significant.

The second assumption in this theory is the limited-capacity assumption (Baddely 1998), which postulates that only a few pieces of information can be actively processed at any one time in each channel. This assumption is in alignment with the cognitive load theory (Sweller 1994), especially since the capacity of the working memory sets narrow limitations. Since the learning of science usually involves diverse concepts and processes, most of them totally new to the learners (Yarden et al. 2004), and requires the generation of large conceptual frameworks (Trowbridge and Wandersee 1996), it faces a considerable challenge to cognition in general and to memory in particular. Hence there is a need in finding tools to assist reducing the inherent cognitive load as well as the organic limited capacities.

The third assumption, the active-processing assumption, states that meaningful learning occurs when the learner engages in active cognitive processes, such as selecting relevant material, organizing it into a coherent representation, and integrating it with existing knowledge (Mayer 1996; Wittrock 1974). This is most likely to occur when the learner has corresponding pictorial and verbal representations in his/her working memory at the same time, thus this theory predicts that multimedia presentations such as narrated animations are most likely to lead to meaningful learning.

According to the Information Delivery Theory of Multimedia Learning (Mayer 1996), the computer is a system for delivering information to learners. When the information is presented in words (such as narration), the learner stores the information in his or her memory. According to this theory, adding multimedia (such as animation) to the verbal information should have no effect on what is learned, if the pictures contain the same information as the words. Thus, according to this theory, multimedia presentations should not result in better learning than single-medium presentations. However, in a mixed situation with learners that prefer visual presentations and others that prefer verbal presentations, a multimedia presentation might be equally effective in delivering information to both kinds of learners. Considering the multiplicity of learning styles students own (Felder 1993), tools such as animations, which can be effective to visual learners as well as verbal learners, might be extremely valuable in teaching and learning science.

Recent advances in information technology and graphics have enabled the development of powerful visualization tools for scientific phenomena and abstract information. The enthusiasm for graphics of all kinds rests on the belief that they can promote comprehension, and foster insights into abstract phenomena (Scaife and Rogers 1996), which are essential for comprehension of various scientific topics. Indeed, this holds especially true for subjects that are naturally spatial, abstract and hard to describe or visualize. Memory has been reported to be greater for pictures than words. Pictures, whether still or dynamic, can facilitate content storage and retrieval under certain conditions (Large 1996).

Distinguishing Between Static and Dynamic Visualizations

While multimedia may be a relatively new technology, the addition of images to text in order to facilitate learning has a much longer history. Pictures can be used to accompany texts in order to improve their comprehensibility and memorability (Large 1996). A number of primary studies in education in general, and in science education in particular, aimed to compare instructional animations with static pictures, and their impact on learning outcomes using meta-analysis. A meta-analysis study is traditionally conducted in three main steps: (1) location and selection of appropriate studies, (2) coding of study features and calculating effect sizes, and (3) statistically analyzing effect sizes and the influence of study features (Hoffler and Leutner 2007).

Using this methodology, Tversky and Morrison (2002) reviewed over 20 primary studies that compared learning from static displays (e.g., pictures) and animations, in order to find the overall-effects of instructional animations compared to static pictures on learning outcomes. Furthermore, factors or variables moderating the effect size were aimed to be identified. Tversky and Morrison (2002) found no advantage of animations over static graphics in most of the studies they investigated. Where a difference was found in favour of the animations, it was because more information was available in the animations than in the static displays. In contrast, another meta-analysis of 26 primary studies, which were published between 1973 and 2003, indicated that in 21 pair wise comparisons, a statistically significant advantage was found in favour of the animations, while the static pictures were significantly superior in only two pair wise comparisons (Hoffler and Leutner 2007).

Obviously, there are some significant differences in the interpretation of information from dynamic vs. static displays, which are not consistently in favour of the dynamic ones. Some of those differences can be explained from the perspective of cognitive load (Sweller 1994). For example, when viewing an animation, "one views one frame at a time, and once the animation or video has advanced beyond a given frame, the previous frame is no longer available to the viewer" (Hegarty 2004, p. 346). This situation may place heavy demand on the working memory, especially in cases when information presented earlier in the animation should be integrated with information that is presented later. In contrast, when viewing a static display, viewers can re-inspect different parts of the display as often as they wish (Ainsworth and Van Labeke 2004). An alternative point of view is that the ability to introduce each step independently in animations reduces the clutter of static illustrations, in which all of the steps are shown at once (Stith 2004).

Individual differences such as spatial ability (Yang et al. 2003) or prior knowledge (ChanLin 2001) can also influence whether static pictures or animations are superior within a specific domain. In the case of low prior content knowledge, learning from molecular representations can be a difficult process (Cook 2006). Students who have little or no knowledge of the domain depend heavily on observable phenomena to construct understanding (Seufert 2003), meaning that they use that which can be easily observed. For that reason, some educational practices favour the use of dynamic visuals over static illustrations because they provide the learners with a ‘ready-made’ explicit and dynamic representation of the situation (Williamson and Abraham 1995). On the other hand, static displays require the learner to construct a dynamic mental model using the static information provided. For instance, students who are expected to learn any kind of change in matter or motion using static visuals have to visualize those changes using static information, whereas when learning from dynamic visuals, the corresponding changes are apparent (Ardac and Akaygun 2005).

From the cognitive-load perspective, the relationship between prior knowledge and visualization format can be conflicting. Although dynamic visuals may reduce the load of cognitive processing by directly supporting the construction of a mental model, their transitory nature may cause higher cognitive load because learners have less control of their cognitive processing (Lewalter 2003). In addition, although animations can provide learners with explicit dynamic information that is unavailable in static graphics, the inclusion of a temporal change in visual displays introduces additional information-processing demands (Lowe 2003). Students with low levels of prior knowledge may find it difficult to extract information from complex animations. Blissett and Atkins (1993) have also reported that individuals with less prior knowledge or lower-ability learners tend to find the learning demands confusing when animation is used.

Even though there is no obvious cognitive advantage to dynamic over static media, most educators and researchers continue to believe that dynamic media have enormous potential for instruction and training (Hegarty 2004). Therefore, the challenge lies in determining what conditions may enable dynamic visualizations to be effective in learning. Mayer and Moreno (2002, p. 88) previously suggested that "Instead of asking, ’Does animation improve learning?’ we should ask ’When and how does animation affect learning?’

Facilitating Students’ Understanding of Molecular Processes Using Animations

Visual representations play a crucial role when complex phenomena are not directly observable. A number of studies related to different disciplines, mostly in chemistry, have shown that instruction involving computer animations can facilitate the understanding of chemical processes at the molecular level. For example, students who had viewed molecular-level computer animations were found less likely to demonstrate the misconception that electrons flow in aqueous solutions without the assistance of ions (Sanger and Greenbowe 1997) than students who had not. In another study, students who viewed animations illustrating the molecular processes of diffusion of perfume molecules in air, and osmosis through a selectively permeable membrane, were less likely to exhibit misconceptions regarding equilibrium, and were less likely to have anthropomorphic views of matter (Sanger et al. 2001). An improved molecular understanding of chemical change was also identified while using dynamic versus static visuals (Ardac and Akaygun 2005). These results favour the use of dynamic visuals over static visuals when presenting molecular representations.

Similarly, in biology, students who viewed an animation on cell death scored significantly higher on the test than those who had not viewed the animation (Stith 2004). In another study, students who viewed a three-dimensional animation of protein synthesis scored significantly higher in a follow-up test than the group that had not viewed the animation (McClean et al. 2005).

Differences in Conceptual Understanding—Using the Conceptual Status Framework

As learning always involves some way of representing information, science teachers make use of different representational techniques in the classroom to communicate ideas to students verbally or visually via texts, images, gestures, and so on (Tsui and Treagust 2007). Representations are simply the way in which we communicate ideas or concepts, by representing them either *externally*—taking the form of spoken language (verbal), written symbols (textual), pictures, physical objects, or a combination of these forms, or *internally*—when we think about these ideas (Hiebert and Carpenter 1992). In this study, we investigated the unique contribution of animation versus still images on students' internal conceptions of molecular processes. For that purpose, we embraced the perspective of conceptual learning (Posner et al. 1982). Conceptions can be regarded as the learner's internal representations, constructed from external ones (Tsui and Treagust 2007). Duit and Glynn (1996) considered conceptions as learners' mental models of an object or event. From the conceptual-change perspective, representability is essential for making difficult concepts more intelligible (Tsui and Treagust 2007).

Conceptual status, an idea built on the conceptual-change foundation, can illuminate deep conceptual learning, whether or not it involves a conceptual change (Hewson and Lemberger 2000). This perspective fits the kind of learning we believe is occurring in our study, in which students are taught, for the first time, about the concepts and procedures involved in the learning of a biotechnological method. Previous studies which analysed students' comprehension of molecular genetics using the conceptual status analysis (Hewson and Lemberger 2000; Tsui and Treagust 2007) suggested that status is a viable hallmark for all conceptual learning.

Research Goal and Questions

The unique contribution of animations versus still images is explored in this paper, in the context of high-school biology students who are studying the PCR method in the framework of learning biotechnology. Individual differences between students, such as their prior content knowledge, which are relevant when learning with static or dynamic visualization tools, were taken into consideration. This study was guided by the following research questions:

1. Is there a difference in the comprehension of PCR between students who learned using animation and those who learned using still images?
2. What are the relationships between students' prior content knowledge and their comprehension of the PCR method, using animation or still images?
3. What is the difference in conceptual status of the PCR method between students who learned using animation and those who learned using still images?

The Context of the Study

The Curriculum

At the end of the 10th Grade, students in Israel choose to major in at least one scientific or non-scientific topic, which is evaluated in a national matriculation examination at the end of 11th and 12th Grades (16–18 years old). The syllabus for biology major studies, 300 h of teaching (Israeli Ministry of Education 2003) includes three compulsory core topics (Systems in the human body, Cell biology and Ecology). In addition, students are required to learn three elective topics, each designed for 30–45 h of teaching. One of the elective topics that teachers can choose is the biotechnology curriculum 'Gene Tamers—Studying Biotechnology through Research' (Falk et al. 2003), which is based on Adapted Primary Literature (APL). Trough this curriculum students are exposed to basic concepts and processes in molecular biotechnology that involve comprehension of several biotechnological methods (Falk et al. 2008).

Visualizing PCR

As a molecular process, PCR is completely invisible and intangible to students. This method is used to make multiple copies of a desired DNA fragment in a test tube, and was developed in 1983 by Kary Mullis who later received a Nobel Prize for his achievement. In the years since Mullis invented the PCR, applications for it have spread throughout the biological sciences (Mullis 1990), as well as used plenty for various applications, including forensic science and genetic testing. The desired DNA may come from a hospital tissue specimen, a single human hair, a drop of dried blood at a crime scene, the tissue of a mummified brain or a 40,000-year-old woolly mammoth frozen in a glacier (Mullis 1990). Since this technique is included in the high-school biology majors' elective biotechnology curriculum in Israel, and given its abstract molecular nature and its impact on biological research, we chose this method as the subject matter of our study.

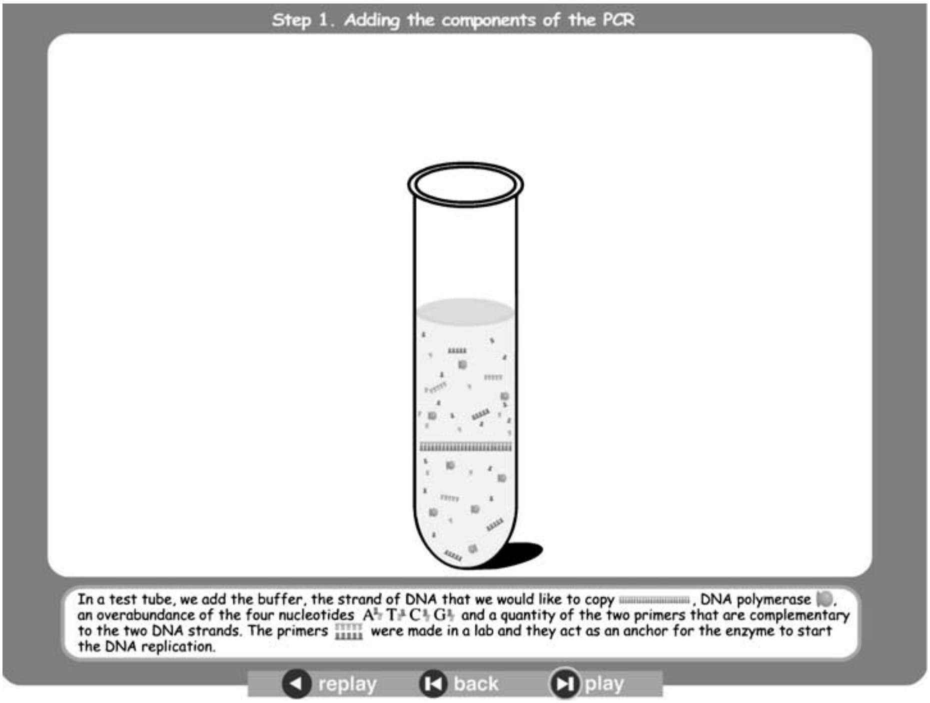
The PCR Animation

The PCR animation (http://stwww.weizmann.ac.il/g-bio/geneengine/animeng/anim_pcr.swf) introduces, sequentially, the procedure of amplifying a desired DNA fragment in a test tube using PCR. The animation starts with the insertion of the relevant materials into a test tube including: the DNA sample, some buffer, the nucleotides, the DNA polymerase enzyme and the primers. The subsequent stages of the animation involve demonstration of the temperature changes—first heating, which induces separation of the DNA strands, then cooling, which enables annealing of the primers to the DNA, and finally, raising the temperature, to allow the process of DNA synthesis. The whole procedure then starts all over again and is repeated a few dozen times.

The developed animation includes written texts, which appear at the bottom of each screen in close proximity to the animation (according to the Spatial Contiguity Principle; (Mayer and Moreno 2002) (Fig. 1). The written texts describe what is being shown in the animation. The texts include images and symbols from the animation itself, accompanied by explanations about what concept each symbol represents.

The Accompanying Computerized Tasks

Components of active learning, such as integrated computerized tasks, seem to be significant in promoting comprehension while viewing animations (Acuna and Sanchez 2004; Kramer et al. 2004). Thus, the developed animation is accompanied by four computerized tasks (http://stwww.weizmann.ac.il/g-bio/geneengine/animeng/anim_pcr.swf). The tasks are aimed at identifying students' attention to key issues in the PCR method, as well as to understanding the symbols and images which appear in the PCR



Step 1. Adding the components of the PCR

In a test tube, we add the buffer, the strand of DNA that we would like to copy , DNA polymerase , an overabundance of the four nucleotides A T C G and a quantity of the two primers that are complementary to the two DNA strands. The primers were made in a lab and they act as an anchor for the enzyme to start the DNA replication.

Fig. 1 A sample frame from the PCR animation. Please note that the original screen contents are in Hebrew

animation. The following assignments were used: matching symbols from the animation with their relevant concepts, putting a list of written stages of the PCR method into the correct order, and putting three pictures, taken from three frames of the animation, into their correct order.

The PCR Cards

A series of cards with still images taken directly from the PCR animation was also developed in the course of this study (see Appendix). The series contains five cards, each card showing a picture taken from a "frozen" frame of the PCR animation, and introducing a central stage of the PCR method. The pictures on the cards are accompanied by the same written text that appears on the relevant frame in the animation.

Research Design and Methodology

Sample

One hundred and seventy-three 12th-grade biology majors participated in this study (107 females and 66 males). The research was conducted from winter 2006 to winter 2007. The students came from nine biology-major classes in five urban high schools in Israel. Five of the nine classes were sampled from the same school, and the other four classes from four different high schools. Prior to the beginning of the curriculum 'Gene Tamers—Studying Biotechnology through Research' enactment (Falk et al. 2003), students in all nine classes had very little, if any, prior knowledge in biotechnology.

The schools and classes participated in this study were chosen according to the teachers' initiative and motivation to take part in the study. All the participating teachers have more than 10 years of teaching experience with the biology majors' syllabus. In addition, all of them participated in an introductory teachers' development summer workshop that took place over three consecutive days (8 h a day), which was aimed at teachers who implement primarily the biotechnology curriculum in their classrooms.

Procedure

In order to find out if an animation per se is a facilitator to learning, we compared it to learning using equivalent static images. Accordingly, a quasi-experimental method, with an experimental group and a comparison group, was used in this study. The experimental group used the PCR animation for learning the PCR method, while the comparison group used the equivalent still images, for learning the PCR method. The equivalent still images were taken directly from the PCR animation and appeared on a series of cards (see a description of the PCR cards above).

At the beginning of the activity with the alternative visualization tools, the students in all nine parallel classes were asked to answer a written questionnaire exploring their prior content knowledge. All of the students were learning about PCR for the first time through these activities, and their teacher had not discussed PCR in advance. Thus, the prior knowledge questionnaire was not about PCR but mostly about DNA replication. Next, students in four classes ($n=83$) received cards with still images taken directly from the PCR animation (still images group—the comparison group) and students in the other five classes ($n=90$) watched the PCR animation (animation group—the experimental group). The animation group was originally divided into two sub-groups: both watched the PCR animation, but in one of the groups the animation was accompanied by three computerized tasks. Since no significant differences were found between the two sub-groups, using an analysis of variance (ANOVA) test, they were re-united into one group for the data analysis. The students in the two treatments then answered a second questionnaire, which examined their understanding of PCR. During learning with the animation as well as with the still images, the students worked in pairs and their conversations were audio-taped. All the questionnaires were filled individually.

Watching an animation or equivalent still images is quite a short procedure. Here, the intervention of viewing the alternative visualization tools lasted three class periods (135 min) in each of the two groups, in order to make the intervention as well as the learning activity most meaningful.

Tools

Both quantitative and qualitative research tools were used in the course of this study in order to probe students' understanding of the PCR method. The quantitative research tools, namely the prior content knowledge questionnaire and the post-intervention questionnaire, were used to check causality and correlation between variables such as students' prior content knowledge and students' understanding of the PCR method. In addition, students' discourses were analysed to gain a deeper understanding of the learning process of PCR using animation or still images.

The Prior Content Knowledge Questionnaire

In this questionnaire, the students were asked to respond to five True/False (T/F) statements and to answer one open question, all designed to examine their prior content knowledge in topics which are relevant to understanding the PCR technique (e.g., DNA replication). The T/F statements were aimed at probing students' understanding of the process of DNA replication and the role of nucleotides in this process. The students were asked to explain their responses to both True and False statements. In the open-ended question, students were asked to write 4 or 5 sentences about how the process of DNA replication occurs in a living cell.

The Post-Intervention Questionnaire

This questionnaire was aimed at examining students' understanding of the PCR method following the activity with the animation or still images. It was composed of three parts:

1. The first part included five T/F sentences, aimed at probing students' understanding of the PCR method in the following issues: the function of the DNA polymerase enzyme, the primers and the nucleotides in the PCR procedure, the specific temperatures used during the different stages of the PCR method, and the outcomes of the PCR method in terms of amount of DNA.
2. In the second part of the questionnaire, the students were asked to compare the DNA replication process that occurs during the PCR procedure to the equivalent process that occurs in a living cell, in terms of the location, the temperatures of the process, the participating enzyme, and the use of nucleotides, primers and the products of the process.
3. The third part of the questionnaire was composed of three open-ended questions, aimed at probing students' understanding of the PCR method by activating high-order cognitive skills, namely analysis and synthesis (Bloom 1956). The students were asked to explain why it is necessary to know the sequence of a gene in order to amplify it by the PCR method, and were asked to give two explanations for the association between the primers and the DNA strands. In the third question, the students were asked to calculate the number of DNA molecules after 5 cycles of the PCR procedure, as well as the number of DNA strands.

A delayed post-intervention questionnaire was not conducted in this study, since learning biotechnological methods is a complex process, which involves the use of various teaching strategies and learning tools, including hands-on labs, guided tours in industrial factories, as well as animations. It was our purpose to focus on the learning episode of learning PCR through the use of alternative visualization tools, animation versus still images, and to investigate the impact of those visualization tools in the course of this episode. However, it did not seem relevant to investigate the specific effects of each of the alternative visualization tools, since it is impossible to separate their impact from that of the other above-mentioned teaching strategies.

Students' Discourse Analysis

While the students watched the PCR animation or viewed the equivalent still images, they worked in pairs and were requested to speak aloud. Their discussions were audio-taped and transcripts of the conversations were prepared. Four transcripts from the animation group and four from the still images group were randomly chosen and qualitatively analyzed based on the conceptual status framework (Hewson and Lemberger 2000; Tsui and Treagust 2007). This framework is based on the notion that the key factor in conceptual learning is the status of a new conception that is held or considered by a learner, according to three conditions of conceptual status. The first condition, *intelligibility*, measures the extent to which the learner knows what the new conception means and can represent it. The next one, *plausibility*, measures the extent to which the learner believes that the new conception is true, and finds it consistent with or is able to reconcile it with other accepted ideas. The third condition, *fruitfulness,* reflects whether the learner finds the new conception useful in solving problems or suggesting new possibilities and directions (Tsui and Treagust 2007). The three conditions of conceptual status are composed of status *elements* (see Table 1). These status elements provide an inventory for categorizing a student's conception and judging whether the status of a certain student's conception meets the conditions of *intelligibility, plausibility* or *fruitfulness* (Hewson and Lemberger 2000).

In practice each transcript from the eight chosen transcripts was divided into episodes based on the scientific content. We used the descriptions of the status elements (Hewson and Lemberger 2000) to identify the specific status elements held by the students through the content episodes. For example, in order to identify the inclusion or exclusion of the status element *image,* which is included in the conceptual status of *intelligibility*, we looked through the discourse to check whether the students have used pictures from the animation or from the still images, to represent their conceptions. Students' metacognitive comments about their conceptions were analyzed in that way as well. To illustrate the explicit inclusion or exclusion of a status element during an episode, it was indicated with a "+" or a "−" sign, respectively. Then the inclusion or exclusion of the status elements was used to identify the conceptual status itself, which represent students' conceptions of the PCR method. For reliability verification, those transcripts were also analyzed by another researcher, with an agreement of 95% between the two researchers.

Results

Comprehension of PCR Using the Various Visualization Tools

The students' comprehension of the PCR method was characterized by comparing the two treatments: students who learned the PCR method using animation (n=90) and those who used still images (n=83). To monitor students' prior content knowledge, which might affect their understanding of the PCR method, we first examined students' prior content knowledge in topics that are relevant to understanding the PCR method. Those topics include DNA replication, nucleotides' functions in the cell, and the function of the DNA polymerase enzyme. The results, obtained using a t-test, indicated no significant differences between the two groups in terms of prior content knowledge (Fig. 2, left). Next, we examined whether the use of different visualization tools affects students' comprehension of the PCR method. By comparing students' mean scores in the post-intervention questionnaires (t-test), we found a significant advantage for the animation group over the still images group (t=4.64, p<0.001, Fig. 2, right). Since no differences were found between students' prior knowledge, we concluded that use of the PCR animation as a visualization tool provides an advantage to learners of the PCR method.

Table 1 Status elements for analyzing conceptual status (Following Tsui and Treagust 2007; Hewson and Lemberger 2000)

Conceptual Status	Status elements
Intelligibility	Representational modes:
	Intelligibility analogy (analogy or metaphor to represent conception)
	Image (use of pictures or diagrams to represent conception)
	Exemplar (real-world exemplar of conception)
	Language (linguistic or symbolic representation of conception)
Plausibility	Consistency factors:
	Other knowledge ('reasoned' consistency with other high-status knowledge)
	Lab experience (consistency with laboratory data or observations)
	Past experience (particular events consistent with conception)
	Epistemology (consistency with epistemological commitments)
	Metaphysics (referring to ontological status of objects or beliefs)
	Plausibility analogy (another conception is invoked)
	Other factors:
	Real mechanism (causal mechanism is invoked)
Fruitfulness	Power (conception has wide applicability)
	Promise (looking forward to what new conception might do)
	Compete (explicitly compare two competing conceptions)
	Extrinsic (associate new conception with experts)

The Relationship Between Students' Prior Content Knowledge and Their Comprehension of PCR

Students' prior knowledge was used here as a moderator variable that enabled elucidating its effect on students' comprehension of the PCR method. We had already learned that there were no significant differences between the treatments in terms of students' prior content knowledge. In order to delve more deeply into the kinds of relationships that may exist between students' prior content knowledge and their comprehension of PCR, students'

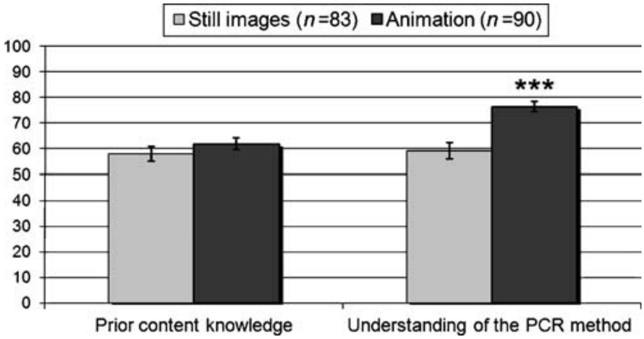


Fig. 2 Comparison between students' mean scores in prior content knowledge and understanding of the PCR method following learning using different visualization tools. The significant differences are marked by *** ($p<0.001$)

scores in the post-intervention questionnaire were correlated with their prior content knowledge, in each of the two groups. In addition, a regression was calculated in students' scores in the prior content knowledge questionnaire.

As can be seen in Fig. 3, a relatively high correlation was found between students' prior knowledge and their understanding of the PCR method in the still images group (R^2= 0.412). Students with a low prior content knowledge achieved low scores in the post-intervention questionnaire, while students with a high level of prior knowledge achieved high scores in the post-intervention questionnaire. In contrast, in the animation group, the level of students' prior content knowledge seemed to have no noteworthy effect on their success in the post-intervention questionnaire, namely on their understanding of the PCR method (R^2=0.0906). As can be clearly seen in Fig. 3, students with a particular score in the prior content knowledge questionnaire, for instance 40 points, achieved low scores in their post-intervention questionnaires if they learned PCR using still images, and higher scores in their post-intervention questionnaires if they learned PCR using the animation. In other words, students' prior content knowledge was found to be an important factor for students who learned PCR using still images, whereby low prior knowledge could serve as an obstacle to learning the PCR. In contrast, the same variable had no noticeable effect on students who learned PCR using animation. Even low prior knowledge did not harm students' ability to learn the PCR method and understand it correctly, if they learned it using animation.

Students' Conceptual Status—a Qualitative Analysis

To gain a deeper understanding of the differences in comprehension of the PCR method between students who learned using animation and those who learned using cards with still images, we employed qualitative research tools to supplement the above-described quantitative ones. We chose to use discourse analysis technique, which is based on analysis of students' conceptual status (Hewson and Lemberger 2000; Tsui and Treagust 2007). Eight transcripts of students' conversations were randomly chosen, four from the animation group and four from the still images group, and subjected to a qualitative analysis of students' conceptual status (as described in detail in the Research Design and Methodology section above).

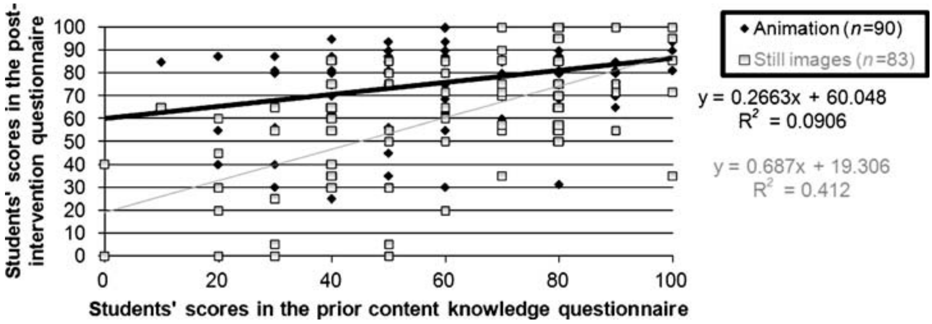


Fig. 3 A regression of students' scores in the prior content knowledge questionnaire, with their scores in the post-intervention questionnaire, in each of the two alternative groups: Animation group (black line) and Still images group (grey line)

The differences in conceptual status between students who learned PCR using animation and those who learned using still images were mostly found in three kinds of content episodes: the function of the DNA polymerase enzyme, the function of the primers, and the specific temperatures at which different stages in the PCR method occur. The differences in students' conceptual status, which were found in each of the three content episodes, are presented below.

The Function of DNA Polymerase

In the content episodes which dealt with the function of DNA polymerase, we found that students who learned the PCR method using animation reflected mostly the following status elements in their conversations: *metaphysics,* which indicates that they referred to the ontological status of DNA polymerase, and *real mechanism,* which indicates that the students understood the causal mechanism in which DNA polymerase is involved. Below are two examples of such episodes, which include the expression of those status elements:

1 The reaction begins by the separation of the two DNA strands... [Reading from the text which accompanies the animation]
2 So [DNA] polymerase is causing the small ones [the nucleotides] *(+image*), right? *(+real mechanism)*
1 Yes, and this is why they put a lot of them [nucleotides], so instead of only two strands there will be a lot of them. *(+real mechanism*)

The students in the above example seem to understand the causal mechanism between DNA polymerase and the nucleotides, namely the creation of new DNA strands using the nucleotides through the synthesis function of the DNA polymerase.

Below we present another example from another conversation, which illustrates students' understanding of the function of DNA polymerase:

1 Does it [the DNA polymerase] separate them [the DNA strands]? [As written in a True/ False statement in the post-intervention questionnaire]
2 No, it does not (+*real mechanism*). It does the replication (+*metaphysics*). Here [watching the animation], now they [the DNA strands] are separating, you see, it [the DNA polymerase] doesn't do the separation; it makes a new DNA (+*metaphysics*).
1 Does it do it at 95°C? [as written in a True/ False statement in the post-intervention questionnaire]
2 No, it does it at 65°C. (+*real mechanism*)

Once again, in this example, the students clearly understood the causal mechanism in which DNA polymerase is involved (+*real mechanism*) or in this case, not involved, as it does not cause the separation of the DNA strands. The students could address DNA polymerase to its exact ontological function, which is the process of DNA replication (+*metaphysics*), and could address the exact temperatures in which this reaction occurs (+*real mechanism*). Since the expression of the status elements of *metaphysics* and *real mechanism* can serve as a mark of the conceptual status of *plausibility* (Hewson and Lemberger 2000), we can assume that students who learned the PCR method using animation understood the function of DNA polymerase in the correct way, and found it consistent with other ideas that they had already accepted, such as DNA replication.

In contrast, in equivalent transcripts from conversations among pairs who learned the PCR method using still images, we discovered that the above-mentioned status elements (*real mechanism* and *metaphysics)* were excluded from their conversations. For example:

1 I did not understand what the DNA polymerase is doing. (-*metaphysics*)
2 It is written [in the text].
1 I did not understand what DNA polymerase is doing (-*metaphysics*), I mean, do they [the primers] stick by themselves?
2 Here, [reading the text] "The DNA polymerase is synthesizing a new DNA strand."
1 What does it mean? They [the primers] are already attached, so what does it [the DNA polymerase] do? (-*metaphysics*)
2 Maybe it [the DNA polymerase] is connecting between them [the primers], I don't know… (-*real mechanism*)

As can be seen in this example, students who learned about PCR using still images did not understand what the DNA polymerase's ontological function was, and raised questions regarding this issue over and over again (-*metaphysics*). In addition, they raised questions and made incorrect statements regarding the mechanism in which DNA polymerase is involved (-*real mechanism*), for example, by suggesting a kind of causal mechanism between DNA polymerase function and the annealing of the primers. Thus, the exclusion of the *metaphysics* and *real mechanism* status elements in the conversations from the still images group can indicate that these students lacked the conceptual status of *plausibility* regarding DNA polymerase; namely, the students who learned about PCR using still images did not understand the function of DNA polymerase in the correct way, and could not reconcile it correctly with other accepted ideas they had, such as DNA replication.

The Function of the Primers

Differences in students' conceptual status between those who learned using animation and those who learned using still images were also found in episodes that dealt with the function of the primers in the PCR method. Upon analyzing qualitatively students' conversations, we realized that this issue was not easy to understand for students in either group. We gained this insight from the number of questions students raised, as well as from misunderstandings they expressed in their statements. Nevertheless, students who learned the PCR method using the animation expressed diverse status elements from two different conceptual statuses. They expressed the status element of *image*, which indicates that they used the pictures that appeared in the animation in order to represent the primers, and the status element of *language*, which indicates that they used linguistic representations of the primers as well. Those two status elements mark the conceptual status of *intelligibility*, which means that the students know what the concept of primers means, and that they can represent it. The students also expressed the afore-mentioned status elements, *metaphysics* and *real mechanism*, marking the higher conceptual status of *plausibility.* Here is a representative example of the expression of such status elements in students' conversations while using the animation:

1 What are primers? [Reading a True/False statement from the post-intervention questionnaire] "Fragments of DNA which serve as enzymes in the reaction of..."
2 They are not enzymes. (+*metaphysics*)
1 Right. They are not enzymes. They are like attaching to the big fragment of DNA, right? (+*real mechanism*)
2 Yes. The primers are those we saw in the beginning [of the animation], which are attached in 45°C, those big small ones (+*image*), I think they are involved in the initial stages of the process (+*language*).

As can be seen in this conversation, the students use the symbols from the animation to represent primers visually (+*image*), and verbally (+*language*). We also find in this conversation that the students understand the ontological status and the function of the primers, by reiterating that they are not enzymes (+*metaphysics*). In addition, the students understand the causal mechanism in which the primers are involved (+*real mechanism*), namely the annealing to the DNA strands. The expression of these latter two status elements indicates that students who used the PCR animation go beyond the conceptual status of *intelligibility* in their understanding of the concept of primers. The students clearly express the next conceptual status of *plausibility,* which means that they not only know what the conception of primers means and can represent it (*intelligibility*), but also believe this conception to be true and find it consistent with other accepted ideas (*plausibility*), such as annealing to the DNA strands.

However, in conversations of pairs who learned about the PCR method using still images, we noticed that the students lacked the high conceptual status of *plausibility*. For example:

1 "The primers are short DNA fragments which serve as enzymes" [reading a True/False question from the post-intervention questionnaire]. It is true. (-*metaphysics*)
2 Yes.
1 They serve as enzymes, right?
2 I think they are. (-*metaphysics*)

We note that this time, as opposed to the case of students who learned using the animation, the students from the still-images' group did not understand the true ontological status of the primers (-*metaphysics*) and believed, incorrectly, that the primers are enzymes.

The Specific Temperatures at Which Different Stages in the PCR Method Occur

The third topic, in which differences in students' conceptual status were found between students who learned PCR using animation and those who learned using still images, dealt with the specific temperatures at which different stages in the PCR method occur. As in the two topics introduced above, pairs who learned the PCR method using animation reflected a variety of status elements in their conversations, most of them indicating the high conceptual status of *plausibility*. For example:

[The students are solving a question in the post-intervention questionnaire. While solving the question they watch the animation.]

1 You see, they [the DNA strands] are heated and are separating...
2 O.K, but in the question they are asking why these [the primers] are attached and not these [the DNA strands]?
1 Because they are smaller (+*real mechanism*). The primers are starting (+*language*), and then the DNA polymerase is helping to complete them [the DNA strands] (+*real mechanism*).

Another example:

1 They are so nice, those polymerases. While the temperature goes down to 45°C, they attach, then to 65°C. The purpose of the 95°C is to separate [between the DNA strands]. (+*real mechanism*)
2 They have been separated, then those primers are placed on those [DNA strands], now the enzyme, I think it is those green ones (+*image*) that will continue to build them (+*real mechanism*).

1 Right, right.
2 Then they will finish building them. Why 65°C? Once again, I did not understand.
1 Look, at 95°C they separate, 45°C, attach, 65°C, the enzyme continues, in order for the two strands of DNA to attach, a temperature of 45°C is needed. (+*other knowledge*)
2 They [the DNA strands] are not attached; it is the primers that are attached. (+*real mechanism*)

As can be clearly seen in these two examples, the students who learned about PCR using animation expressed status elements in their conversations such as *image* and *language*, which indicate owning the conceptual status of *intelligibility*. Moreover, status elements such as *other knowledge* and *real mechanism* are also expressed in the conversation, showing that these students also gained the conceptual status of *plausibility*. The students showed that they already know that annealing to the DNA strands occurs at 45°C, and stated that in the PCR, the primers anneal to the complementary DNA strands and, much less frequently, the strands anneal to themselves, because of the primers' size (+*real mechanism*). Thus, the students who learned PCR using animation clearly demonstrate that they understand mechanistic aspects of PCR, and that they find them consistent with other accepted ideas, such as DNA replication.

In contrast, in conversations involving pairs who used still images while learning the PCR method, the status elements of the conceptual status of *plausibility* were usually excluded. For example:

1 "Separation of the strands and annealing of the primers" [reading the title of the second card]. "The reaction begins by heating the mixture…[reading the accompanying text].
2 DNA polymerase is this green color, the enzyme. (+*image*)
1 Yes, polymerase. After they heat they…
2 No, no, it is not. This and this [the DNA strands] are separating, and they are [the nucleotides] attaching.
1 Yes, T A C G. (+*image*)
2 Then what did we get? (-*real mechanism*)
1 Wait, these are the primers, wait, after 45°C, "we heat the mixture to 65°C" [continue reading].
2 "We end up with a new DNA" [reading from the text], but…, read again.
1 "We heat the mixture to 65°C. At this temperature, the DNA polymerase creates… At the end of this cycle, we end up with two copies of the original double-stranded DNA molecule" [reading from the text].
2 Well, no, I did not understand it (-*real mechanism*). Move, move to the next card…

As can be seen in this example, the students who used the cards with the still images expressed confusion and misunderstanding in their conversation. These students used different symbols which appeared in the animation in order to represent concepts such as DNA polymerase and the nucleotides (+*image)*. This probably indicates that they own the conceptual status of *intelligibility*, meaning that they know what those concepts mean, and are able to represent them. On the other hand, when it comes to higher conceptual demands, such as understanding the causal mechanism in which those concepts are involved (*real mechanism*), the students who learned about PCR using still images do not understand what happens when the DNA strands separate (-*real mechanism*). In fact the whole conversation is based on reading the text that accompanied the still images over and over, in an almost desperate attempt to understand what happens, which ends in despair and moving to the next card.

Here is another example from another conversation, in which the students are trying to understand the same issue:

1 I did not understand, what is the basis of the attachment between the primers and the DNA strands? It can only be hydrogen bonds, I mean, after it [DNA polymerase] is starting to transcribe (*-real mechanism*) it is hydrogen bonds, could it be that there is something on the primers, I do not know, is there any enzyme on the primers or something else? (*-real mechanism*)
2 It is not written [in the accompanying text], it seems to me it cannot be attached to it [the primer to the DNA strand], it is not complementary, it is the same. (*-metaphysics*)
1 It is written [in the text] that at 95°C they [the DNA strands] separate, and then it is written that at 45°C they [the primers] are attached, and the question [in the post-intervention questionnaire] is why is it the primers and not the DNA strands?
2 Because this is not the temperature which is aimed to attach them, we probably need another temperature. (*-real mechanism*)
1 Maybe 45°C is not the optimal temperature for the polymerase.
2 So maybe 45°C is not the optimal temperature for attaching the strands by DNA polymerase. (*-real mechanism*)
1 We are asked [in a question in the post-intervention questionnaire] to write two explanations, so we can write what we want, so write that between the two DNA strands there are different bonds than between the strands and the primers. (*-real mechanism*)

In this example, we can see once again how the students depend on the text, this time through their attempts to understand why after the separation of the DNA strands, the primers anneal to the complementary strands and not the strands to themselves. Diverse misunderstandings are revealed in this conversation, such as the students thinking that the DNA polymerase is involved in transcription (*-real mechanism*), that the primers are not complementary to the DNA strands (*-metaphysics*) and that a specific temperature is the cause of this association (*-real mechanism*). The exclusion of such status elements from the two examples discussed above indicates that students who learned the PCR method using still images may have learned the main concepts of PCR, and can represent them (*intelligibility*), as indicated mostly in the first example, they do not seem to have understood the interactions between the concepts, and could not find them consistent with other accepted ideas, for example DNA replication.

We can therefore conclude that since the most often excluded status elements in the conversations of the still images group were *metaphysics* and *real mechanism*, it appears that these students were having difficulty understanding the ontological function of the different molecules involved in the PCR method, and the causal mechanism in which they are involved. We also learned that conversations from the still images group were generally based on reading the text which accompanied the still images over and over again, treating it as a crucial source which will enable them to reach understanding. In contrast, use of the animation gave the students an advantage in understanding those aspects of the PCR method.

Students' Conceptual Status—a Quantitative Analysis

Following the qualitative analysis of the students' discourse using the conceptual status framework, we subjected the data to quantitative analysis. First, we gathered all the status elements which were identified in each of the groups' discourses analysed qualitatively above. We identified 65 status elements in the analysed discourses from the animation group, and 32 status elements in the equivalent discourses from the still images group. The length of the discourses in both groups was approximately equivalent (about 50 sentences on average in each discourse). We then grouped the status elements identified in each of the treatments under the relevant conceptual status: intelligibility, plausibility or fruitfulness (see Table 1). A $\chi 2$ test was used to trace possible differences between the animation and still images groups, in each of the three conceptual statuses.

As can be seen in Fig. 4a, b, a significant advantage for the animation group compared to the still images group was identified in the conceptual status category of *plausibility* ($\chi 2=26.19$, $p<0.0001$). The differences were reflected in terms of the significant differences in both inclusions of status elements from the *plausibility* conceptual status, in favour of the animation group, and exclusions of the same status elements of the *plausibility* conceptual status in conversations from the still images group. The specific status elements were *real mechanism* and *metaphysics*, the same status elements whose

Fig. 4 Comparison between students' conceptual status, following learning using different visualization tools. The n represents the number of status elements that was identified in each of the two groups' discourses. + represents the inclusions of status elements, while–represents the inclusion of the status elements. The data was analyzed using $\chi 2$ test. The significant differences are marked by *** ($p<0.0001$)

recurrent appearance in conversations from the animation group, and absence in conversations from the still images groups, had been reported and demonstrated in the qualitative analysis of the students' discourses.

From the quantitative analysis of students' conceptual status we also learned that students from both groups had reached the kind of understanding reflected by the conceptual status of *intelligibility*, meaning they knew what the concepts of PCR mean, and they could represent them using images, language or examples. However, the next level of understanding, which is reflected by owning the *plausibility* conceptual status, appeared to be available only to the students who watched the animation. As it was expressed in their conversations, the students who used the animation were able to understand the causal relationships between different molecules in the PCR method, as well as the ontological function of those molecules. Regarding the third and highest conceptual status of *fruitfulness*, it appears that neither group reached this level of understanding; they did not reveal significantly in their conversations that they had found the concepts of the PCR method useful in solving problems, or in suggesting new possibilities and directions. Considering the fact that the students in our study are learning about PCR for the first time, using the alternative visualization tools, this finding is very reasonable. However, the fact that we did find a few inclusions of status elements from the *fruitfulness* conceptual status in conversations of students who learned using the animation is appealing and encouraging. We therefore believe that in the subsequent stages of learning PCR more deeply, those inclusions could become apparent.

Discussion and Conclusions

Our research is aimed at studying the contribution of animations of biotechnological methods in general, and of the PCR method in particular, on students' conceptual learning of those methods. In the course of our study, we compared the impact of using animation versus equivalent still images developed from the animation on students' outcomes, in terms of their content knowledge and conceptual status while using dynamic versus static visualization tools. The use of the PCR animation as a visualization tool was shown here to provide a significant advantage to the students who used it over those who used still images. Even though there is a lack of clarity regarding the unique advantages of animations (Hegarty 2004; Tversky and Morrison 2002), some studies have already shown that dynamic displays can be particularly effective when learning content that requires the students to visualize motion (Reiber 1990). Studies that tested the effectiveness of animations versus still images on students' understanding of contents that require visualization of motion at the molecular level have also shown significantly higher understanding for students who used dynamic visuals (Ardac and Akaygun 2005; Williamson and Abraham 1995). We believe that in this matter, our study supports the use of animations over still images, when the type of knowledge to be acquired can be classified as dynamic, particularly in demonstrations of molecular phenomena. The question that remains is what the distinctive advantages of animation are when visualizing motion.

According to Reiber (1990), the degree of visual elaboration required to convey a complete image might play an important role in explaining the differential learning effects observed for dynamic versus static visuals. One major advantage of dynamic visuals is that they enable a display of the collective motion of particles, which can be effective in conveying a complete mental image of changes in matter (Ardac and Akaygun 2005). In the present study, our goal was to facilitate students' understanding of the interactions between various molecules in the course of the PCR, by relating them to the corresponding symbolic representations, which were identical in the animation and on the cards with the still images. Our results imply that for such tasks, the animation serves as a better alternative than the static visuals.

A more detailed picture of the distinct advantages of animation was obtained by analyzing qualitatively students' discourse, in the framework of a conceptual status analysis. Students' discourse was not only important as a data source for the qualitative research approach, but it was also valuable in examining students' integration of knowledge while learning PCR using alternative visualization tools. According to Kozma and Russell (1997), verbal explanations play a fundamental role in the development of an integrated knowledge base, acting like a 'semantic glue' that holds different representations together. In his study, Kozma (2000) claimed that students should work in rich social contexts that prompt them to interact with each other and with multiple systems, to create meaning for chemical phenomena.

Comparing the relative frequency of diverse status elements in the conversations of students from both groups, we identified recurrent inclusions of the status elements *metaphysics* and *real mechanism* in conversations of students who learned about PCR using animation. However, in conversations of students from the still images group, these status elements were absent, and the students reflected misunderstandings in those aspects. The two specific status elements of *metaphysics* and *real mechanism* represent the learners' ability to understand the ontological function of different molecules, and the causal mechanism that invokes them, respectively. According to Guenther (1998), the ability to understand the essential parts of a system, and the cause-effect relationships that exist within it, are the two most important roots of conceptual learning. Being able to reason causality is an essential cognitive skill that is central when learning scientific topics, since the core properties of all sciences are causally related in nature (Carey 2002). Reasoning causality enables us to predict, infer, and explain the events or phenomena that we encounter or observe (Hung and Jonassen 2006).

The differences in the conceptual status in favour of students who learned PCR using animation were mostly found in three topics, which can be classified as mechanistic aspects of the PCR method. Accordingly, students' explanations during those conversations can be classified as mechanistic explanations. A mechanistic explanation is "An explanatory account of observed results by describing the mediating process by which the target factor could have produced the effect" (Koslowski et al. 1989). Hung and Jonassen (2006) focused on ways to enhance conceptual understanding of physics; they showed that students who learned using a mechanism-based approach significantly outperformed the other two experimental and control groups. The mechanistic principle is one of the three main principles that validate a causal relationship, the latter serving as the foundation for the processes of conceptual learning (Hung and Jonassen 2006). Since we were able to show that mechanistic aspects were repeatedly reflected in conversations of students who learned about PCR using animation, and were absent from conversations of students who learned using still images, we can state that the use of the animation did enable the students to achieve a conceptual understanding of the PCR.

The role of students' prior knowledge, while learning PCR using dynamic or static visualization tools, was another aspect investigated in the course of this study. Students' prior content knowledge was found to be an indispensable factor for students who learned about PCR using still images. In contrast, the level of students' prior content knowledge did not appear to have any notable effect on their understanding of PCR while learning using animation; accordingly, a low level of prior knowledge did not serve as an obstacle to students from the animation group, as opposed to those from the still images group.

One explanation might be that since animations help in mentally visualizing a process or a procedure, they reduce the cognitive effort required in comparison to static pictures, in which the process has to be reconstructed from the pictorial information (Hoffler and Leutner 2007). This might explain our finding that students' prior content knowledge was a crucial factor for students who learned about PCR using still images. The explicit, "expert-like", dynamic representation of the situation, as it appears in animations, might also explain why during their use, there is less dependence on prior knowledge, as opposed to when static illustrations are used (Williamson and Abraham 1995). The dynamic display of a process by animation can also compensate for a student's insufficient knowledge in imagining some relevant motions (Salomon 1979).

Looking at this issue from an alternative point of view, Lewalter (2003) claimed that since dynamic visuals may reduce the load of cognitive processing by directly supporting the construction of a mental model, this might result in learners having less control of their cognitive processing. Mayer et al. (2005), in a study examining the use of annotated illustrations versus narrated animations, found that static illustrations with printed text promote germane processing as compared to narrated animations. Germane processing is the cognitive processing that involves deeper processing of the key material by mentally organizing it into a coherent cognitive representation and integrating it with other representations and prior knowledge (Sweller 1994). According to Mayer et al. (2005), the advantage of the static-media presentation is that it encourages generative processing, such as mentally animating or self-explaining the key changes from one static frame to the next. These authors suggested that animations should be constructed or used in ways that tap the positive features of static illustrations. For example, learners could be encouraged to engage in active processing through activities, such as generating explanations or answering questions, during learning using the animation. In addition, according to de Jong et al. (1999), instruction through computer simulation should use further prompting to support students' regulative processes.

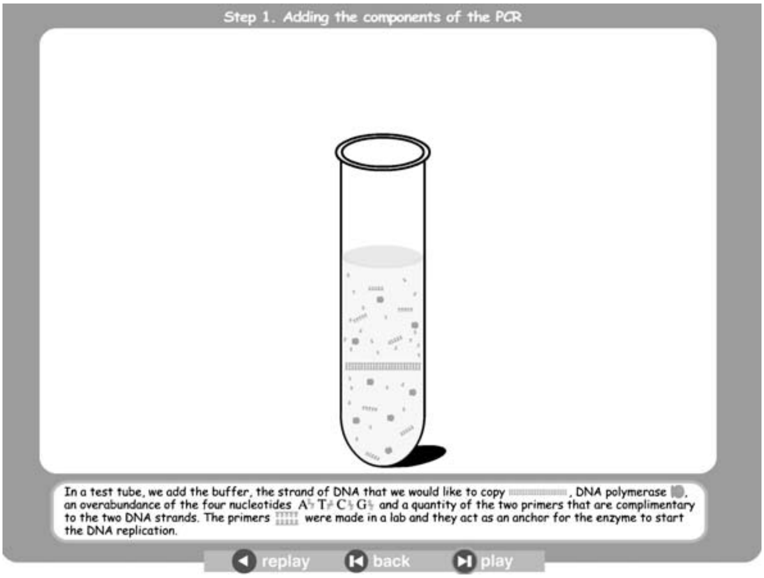
The role of prior knowledge as a central element of active cognitive construction is well known from the constructivist perspective (Ausubel 1963; Glasersfeld 1998). According to this perspective, learning is the product of self-organization (Glasersfeld 1998), in which prior knowledge is one of the major building blocks. Our study shows that prior knowledge is not an essential factor when learning using animation. Indeed, there are several benefits, mostly at the initial stages of learning, with the presentation of an explicit, "ready-made" "expert-like" external representation, as it appears in the animation. But for the sake of the long-term benefits, we think that effort should be made in making the visual exploration while watching animations more active in terms of students' use, specifically in involving the students' prior knowledge in a more significant way. For that purpose, we believe that the way in which a teacher enacts the animation in class plays a crucial role. Constructivist teachers tend to explore how their students see any problem or issue they encounter, and why their path towards understanding seems promising to them (Glasersfeld 1998). Thus, the role of the teacher in enacting the animations in class is extremely important and should be further examined.

In conclusion, through this research we were able to show the unique contribution of animation, and its advantage over still images, for the acquisition of certain kinds of information, namely the mechanistic aspects of biotechnological methods. In addition, we showed the unique contribution of animations to certain kinds of learners, namely students with low prior content knowledge. Caution is needed in identifying the implications of this study for the teaching and learning of biology in high school, since it should be kept in mind that in this study we deliberately excluded the teachers' input. It is clear that in practice the use of animations will be mediated to the students by their biology teacher, using various teaching strategies that may have a significant influence on students' comprehension. Nevertheless, we believe our findings regarding the effectiveness of animations when visualizing processes can be extended beyond the context of biotechnological methods, to other diverse topics and processes that involve motion and include interactions between different key factors. Such processes might include macroscopic interactions, for instance, from the disciplines of ecology or mechanics, as well as molecular processes, which are not visible in the real world.

Acknowledgments We thank the graphic designers who enabled us to develop the animations, as well as the students and teachers who participated in this study. Author is the incumbent of the Helena Rubinstein Career Development Chair.

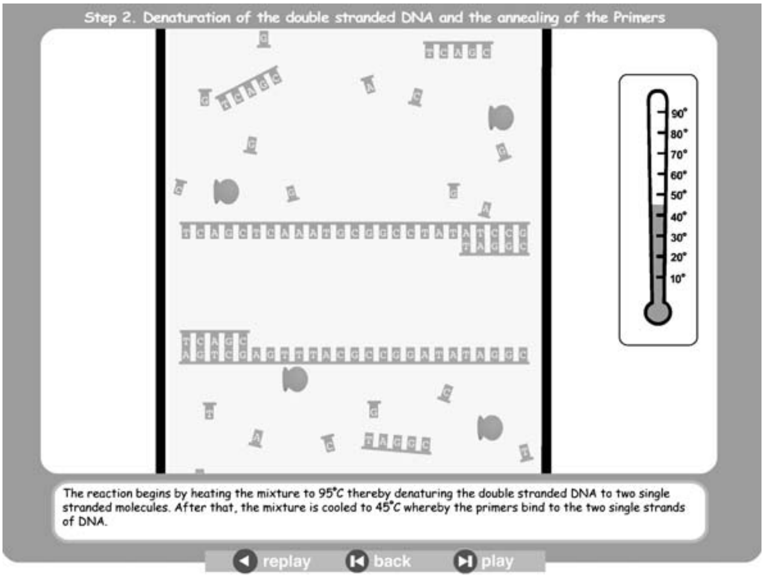
Appendix

The series of 5 cards with the still images used in this research.



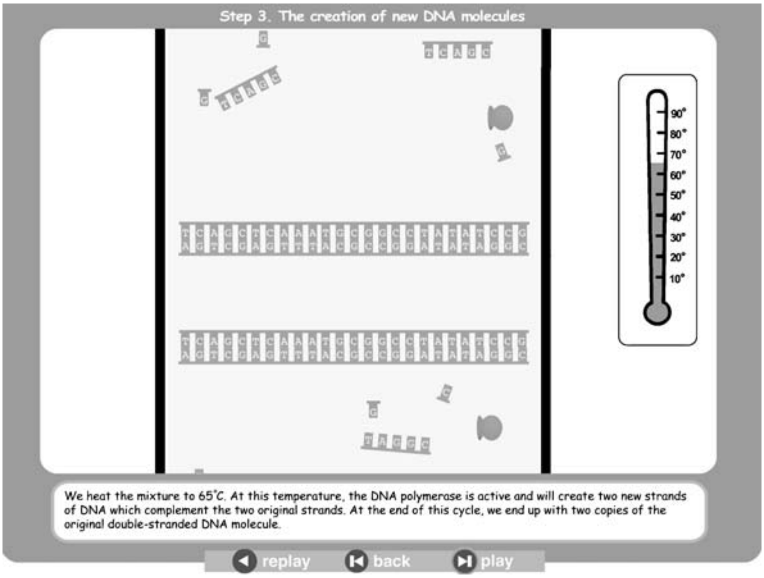
Step 1. Adding the components of the PCR

In a test tube, we add the buffer, the strand of DNA that we would like to copy, DNA polymerase, an overabundance of the four nucleotides A T C G and a quantity of the two primers that are complimentary to the two DNA strands. The primers were made in a lab and they act as an anchor for the enzyme to start the DNA replication.



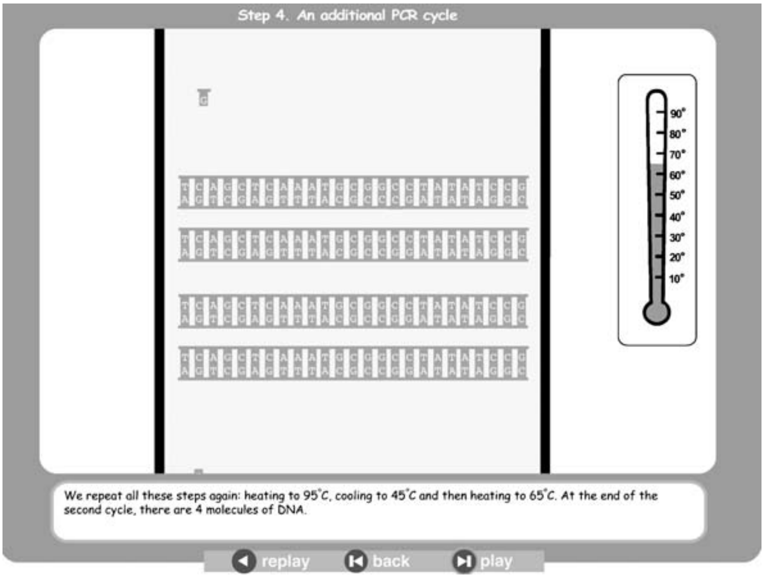
Step 2. Denaturation of the double stranded DNA and the annealing of the Primers

The reaction begins by heating the mixture to 95°C thereby denaturing the double stranded DNA to two single stranded molecules. After that, the mixture is cooled to 45°C whereby the primers bind to the two single strands of DNA.



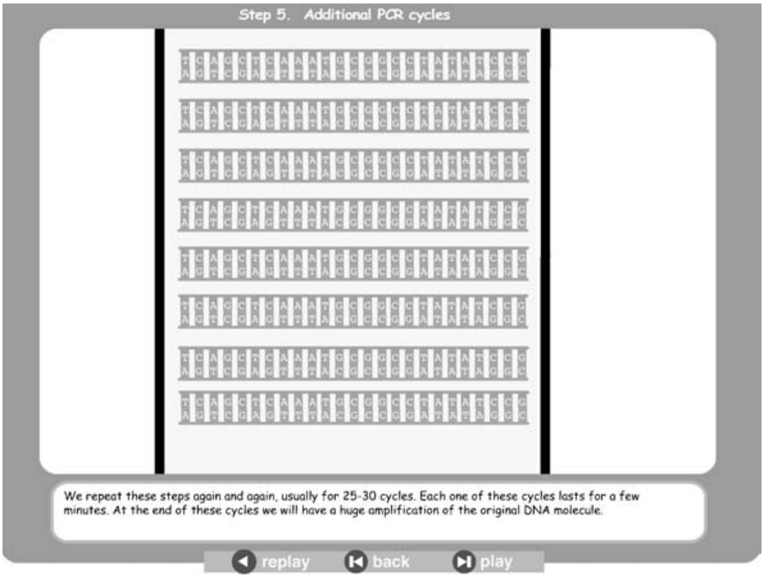
Step 3. The creation of new DNA molecules

We heat the mixture to 65°C. At this temperature, the DNA polymerase is active and will create two new strands of DNA which complement the two original strands. At the end of this cycle, we end up with two copies of the original double-stranded DNA molecule.



Step 4. An additional PCR cycle

We repeat all these steps again: heating to 95°C, cooling to 45°C and then heating to 65°C. At the end of the second cycle, there are 4 molecules of DNA.



Step 5. Additional PCR cycles

We repeat these steps again and again, usually for 25-30 cycles. Each one of these cycles lasts for a few minutes. At the end of these cycles we will have a huge amplification of the original DNA molecule.

References

Acuna, S. R., & Sanchez, E. (2004). "*Dialogic*" *helps to learning with hypermedia*. Valencia, Spain: Paper presented at the European Association for Research on Learning and Instruction (EARLI) SIG2 meeting.

Ainsworth, S., & Van Labeke, N. (2004). Multiple forms of dynamic representations. *Learning and Instruction*, *14*, 241–255. doi:10.1016/j.learninstruc.2004.06.002.

Ardac, D., & Akaygun, S. (2005). Using static and dynamic visuals to represent chemical change at molecular level. *International Journal of Science Education*, *27*(11), 1269–1298. doi:10.1080/09500690500102284.

Ausubel, D. P. (1963). *The psychology of meaningful verbal learning*. New York: Grune & Stratton.

Baddely, A. (1998). *Human Memory*. Boston: Allyn and Bacon.

Bahar, M., Johnstone, A., & Sutcliffe, R. G. (1999). Investigation of students' cognitive structure in elementary genetics through word association tests. *Journal of Biological Education*, *33*, 134–141.

Blissett, G., & Atkins, M. (1993). Are they thinking? Are they learning? A study of the use of interactive video. *Computers & Education*, *21*, 31–39. doi:10.1016/0360-1315(93)90045-K.

Bloom, B. S. (1956). *Taxonomy of Educational Objectives*. New York: David McKay Co Inc.

Carey, S. (2002). The origin of concepts: Continuing the conversation. In N. L. Stein, P. J. Bauer, & M. Rabinowitz (Eds.), *Representation, memory, and development: Essays in honor of Jean Mandler* (pp. 43–52). Mahwah, NJ: Erlbaum.

ChanLin, L. J. (2001). Formats and prior knowledge on learning in a computer-based lesson. *Journal of Computer Assisted Learning*, *17*, 409–419. doi:10.1046/j.0266-4909.2001.00197.x.

Conner, L. (2000). *The significance of an approach to the teaching of societal issues related to biotechnology*. New Orleans, LA, USA: Paper presented at the Annual Meeting of the American Educational Research Association.

Cook, M. P. (2006). Visual representations in science education: The influence of prior knowledge and cognitive load theory on instructional design principles. *Science Education*, *90*(6), 1073–1091. doi:10.1002/sce.20164.

de Jong, T., Martin, E., Zamarro, J., Esqembre, F., Swaak, J., & Van Joolingen, W. (1999). The integration of computer simulation and learning support: An example from the physics domain of collisions. *Journal of Research in Science Teaching*, *36*(5), 597–615. doi:10.1002/(SICI)1098-2736(199905)36:5<597::AID-TEA6>3.0.CO;2-6.

Duit, R., & Glynn, S. (1996). Mental modeling. In G. Welford, J. Osborne, & P. Scott (Eds.), *Research in science education in Europe: Current issues and themes* (pp. 166–176). London: Falmer.

Edmonston, J. (2000). The biotechnology revolution: Distinguishing fact from fantasy and folly? *Australian Science Teachers' Journal*, *46*(4), 11–16.

Falk, H., Piontkevitz, Y., Brill, G., Baram, A., & Yarden, A. (2003). *Gene Tamers: Study Biotechnology Through Research* (in Hebrew). Rehovot, Israel: The Amos de-Shalit Center for Science Teaching.

Falk, H., Brill, G., & Yarden, A. (2008). Teaching a biotechnology curriculum based on adapted primary literature. *International Journal of Science Education*, *30*(14), 1841–1866.

Felder, R. (1993). Reaching the second tier: Learning and teaching styles in college science education. *Journal of College Science Teaching*, *23*(5), 286–290.

France, B., & Gilbert, J. K. (2005). *A model for communication about biotechnology*. Rotterdam: Sense Publishers in cooperation with The New Zealand Biotechnology Learning Hub.

Glasersfeld, E. (1998). Cognition, construction of knowledge, and teaching. In M. R. Matthews (Ed.), *Constructivism in Science Education* (pp. 11–30). Netherlands: Kluwer Academic Publishers.

Guenther, R. K. (1998). *Human cognition*. Upper Saddle River, NJ: Prentice Hall.

Hegarty, M. (2004). Dynamic visualizations and learning: Getting to the difficult questions. *Learning and Instruction*, *14*, 343–351. doi:10.1016/j.learninstruc.2004.06.007.

Hennessy, S., Deaney, R., & Ruthven, K. (2006). Situated expertise in integrating use of multimedia simulation into secondary science teaching. *International Journal of Science Education*, *28*(7), 701–732. doi:10.1080/09500690500404656.

Hewson, P., & Lemberger, J. (2000). Status as the hallmark of conceptual learning. In R. Millar, J. Leach, & J. Osborne (Eds.), *Improving science education: The contribution of research* (pp. 110–125). Buckingham, UK: Open university press.

Hiebert, J., & Carpenter, T. P. (1992). Learning and teaching with understanding. In D. A. Grouws (Ed.), *Handbook of research in mathematics teaching and learning* (pp. 65–97). New York: Macmillan.

Hoffler, T. N., & Leutner, D. (2007). Instructional animation versus static pictures: A meta-analysis. *Learning and Instruction*, *17*(6), 722–738. doi:10.1016/j.learninstruc.2007.09.013.

Hung, W., & Jonassen, D. H. (2006). Conceptual understanding of causal reasoning in physics. *International Journal of Science Education*, *28*(13), 1601–1621. doi:10.1080/09500690600560902.

Israeli Ministry of Education (2003). Syllabus of biological studies: Jerusalem, Israel, State of Israel Ministry of Education Curriculum Center (in Hebrew). See www.bioteach.snunit.k12.il/upload/.bb.

Israeli Ministry of Education (2005). Syllabus of biotechnological studies: Jerusalem, Israel, State of Israel Ministry of Education Curriculum Center (in Hebrew). See www.biotech.ort.org.il.

Kelly, R. M., & Jones, L. L. (2007). Exploring how different features of animations of sodium chloride dissolution affect students' explanations. *Journal of Science Education and Technology*, *16*, 413–429. doi:10.1007/s10956-007-9065-3.

Koslowski, B., Okagaki, L., Lorenz, C., & Umbach, D. (1989). When covariation is not enough: The role of causal mechanism, sampling method, and sample size in causal reasoning. *Child Development*, *60*, 1316–1327. doi:10.2307/1130923.

Kozma, R. (2000). The use of multiple representations and the social construction of understanding in chemistry. In M. J. Jacopson, & R. B. Kozma (Eds.), *Innovations in Science and Mathematics Education* (pp. 11–45). Mahwah, NJ: Lawrence Earbaum Associates.

Kozma, R. (2003). The material features of multiple representations and their cognitive and social affordances for science understanding. *Learning and Instruction*, *13*(2), 205–226. doi:10.1016/S0959-4752(02)00021-X.

Kozma, R., & Russell, J. (1997). Multimedia and understanding: Expert and novice responces to different representations of chemical phenomena. *Journal of Research in Science Teaching*, *34*(9), 949–968. doi:10.1002/(SICI)1098-2736(199711)34:9<949::AID-TEA7>3.0.CO;2-U.

Kramer, B., Prechtl, H., & Bayrhuber, H. (2004). *Using micro-tasks to foster the understanding of signal transduction in a multimedia learning environment*. Patras, Greece: Paper presented at the Paper presented at the European Researchers in the Didactics of Biology (ERIDOB) meeting.

Large, A. (1996). Computer animation in an instructional environment. *Library & Information Science Research*, *18*, 3–23. doi:10.1016/S0740-8188(96)90028-6.

Lewalter, D. (2003). Cognitive strategies for learning from static and dynamic visuals. *Learning and Instruction*, *13*, 177–189. doi:10.1016/S0959-4752(02)00019-1.

Lewis, J., & Wood-Robinson, C. (2000). Genes, chromosomes, cell division and inheritance-do students see any relationship? *International Journal of Science Education*, *22*(2), 177–195. doi:10.1080/095006900289949.

Lock, R., Miles, C., & Hughes, S. (1995). The influence of teaching on knowledge and attitudes in biotechnology and genetic engineering contexts: Implications for teaching controversial issues and the public understanding of science. *Secondary Science Review*, *76*(276), 47–59.

Lowe, R. (2003). Animation and learning: selective processing of information in dynamic graphics. *Learning and Instruction*, *13*, 157–176. doi:10.1016/S0959-4752(02)00018-X.

Maclellan, E. (2005). Conceptual learning: The priority for higher education. *British Journal of Educational Studies*, *53*(2), 129–147. doi:10.1111/j.1467-8527.2005.00287.x.

Marbach-Ad, G. (2001). Attempting to break the code in students' comprehension of genetic concepts. *Journal of Biological Education*, *35*(4), 183–189.

Mayer, R. (1996). Learners as information processors: Legacies and limitations of educational psychology's second metaphor. *Educational Psychologist*, *31*, 151–161. doi:10.1207/s15326985ep3103&4_1.

Mayer, R., & Moreno, R. (2002). Animations as an aid to multimedia learning. *Educational Psychology Review*, *14*(1), 87–99. doi:10.1023/A:1013184611077.

Mayer, R., Hegarty, M., Mayer, S., & Campbell, J. (2005). When static media promote active learning: Annotated Illustrations versus narrated animations in multimedia instruction. *Journal of Experimental Psychology. Applied*, *11*(4), 256–265. doi:10.1037/1076-898X.11.4.256.

McClean, P., Johnson, C., Rogers, R., Daniels, L., Reber, J., Slator, B. M., et al. (2005). Molecular and cellular biology animations: Development and impact on student learning. *Cell Biology Education*, *4*, 169–179. doi:10.1187/cbe.04-07-0047.

Mullis, K. B. (1990). The unusual origin of the polymerase chain reaction. *Scientific American*, *262*, 36–43.

Olsher, G., Berl, D. B., & Dreyfus, A. (1999). Biotechnologies as a context for enhancing junior high-school students' ability to ask meaningful questions about abstract biological processes. *International Journal of Science Education*, *21*(2), 137–153. doi:10.1080/095006999290750.

Paivio, A. (1986). *Mental representations: A dual coding approach*. New York: Oxford University Press.

Posner, G. J., Strike, K. A., Hewson, P. W., & Gertzog, W. A. (1982). Accommodation of a scientific conception: toward a theory of conceptual change. *Science Education*, *66*(2), 221–227.

Reiber, L. (1990). Using computer animated graphics in science instruction with children. *Journal of Educational Psychology*, *82*(1), 135–140. doi:10.1037/0022-0663.82.1.135.

Reiber, L. (1991). Animation, incidental learning and continuing motivation. *Journal of Educational Psychology*, *83*(3), 318–328.

Salomon, G. (1979). *Interaction of media, cognition, and learning*. San Francisco: Jossey-Bass.

Sanger, M. J., & Greenbowe, T. J. (1997). Common student misconceptions in electrochemistry: Galvanic, electrolytic, and concentration cells. *Journal of Research in Science Teaching*, *34*(3), 377–398. doi:10.1002/(SICI)1098-2736(199704)34:4<377::AID-TEA7>3.0.CO;2-O.

Sanger, M. J., Brecheisen, D. M., & Hynek, B. M. (2001). Can computer animations affect college biology students' conceptions about diffusion & osmosis? *The American Biology Teacher*, *63*(2), 104–109. doi:10.1662/0002-7685(2001)063[0104:CCAACB]2.0.CO;2.

Scaife, M., & Rogers, Y. (1996). External cognition: how do graphical representations work? *International Journal of Human-Computer Studies*, *45*, 185–213. doi:10.1006/ijhc.1996.0048.

Seufert, T. (2003). Supporting coherence formation in learning from multiple representations. *Learning and Instruction*, *13*(2), 227–237. doi:10.1016/S0959-4752(02)00022-1.

Solomon, J. (2001). Teaching for scientific literacy: What could it mean. *The School Science Review*, *82* (300), 93–96.

Steele, F., & Aubusson, P. (2004). The challenge in teaching biotechnology. *Research in Science Education*, *34*, 365–387. doi:10.1007/s11165-004-0842-1.

Stith, B. J. (2004). Use of animation in teaching cell biology. *Cell Biology Education*, *3*, 181–188.

Sweller, J. (1994). Cognitive load theory, learning difficulty, and instructional design. *Learning and Instruction*, *4*, 295–312. doi:10.1016/0959-4752(94)90003-5.

Trowbridge, J. E., & Wandersee, J. H. (1996). How do graphics presented during college biology lessons affect students' learning? *Journal of College Science Teaching*, *26*(1), 54–57.

Tsui, C.-Y., & Treagust, D. F. (2007). Understanding genetics: Analysis of secondary students' conceptual status. *Journal of Research in Science Teaching*, *44*(2), 205–235. doi:10.1002/tea.20116.

Tversky, B., & Morrison, J. B. (2002). Animation: can it faciliate? *International Journal of Human-Computer Studies*, *57*, 247–262. doi:10.1006/ijhc.2002.1017.

Williamson, V. M., & Abraham, M. R. (1995). The effects of computer animation on the particulate mental models of college chemistry students. *Journal of Research in Science Teaching*, *32*, 521–534. doi:10.1002/tea.3660320508.

Wittrock, M. C. (1974). Learning as a generative activity. *Educational Psychology*, *11*, 87–95.

Yang, E. M., Andre, T., & Greenbowe, T. Y. (2003). Spatial ability and the impact of visualization/animation on learning electrochemistry. *International Journal of Science Education*, *25*, 329–349. doi:10.1080/09500690210145738b.

Yarden, H., Marbach-Ad, G., & Gershony, J. M. (2004). Using the concept map technique in teaching introductory cell biology to college freshmen. *Bioscene-Journal of college biology education*, *30*(1), 3–13.