Can Dynamic Visualizations Improve Middle School Students' Understanding of Energy in Photosynthesis?

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Abstract: Dynamic visualizations have the potential to make abstract scientific phenomena more accessible and visible to students, but they can also be confusing and difficult to comprehend. This research investigates how dynamic visualizations, compared to static illustrations, can support middle school students in developing an integrated understanding of energy in photosynthesis. Two hundred 7th-grade students were randomly assigned to either a dynamic or a static condition and completed a web-based inquiry unit that encourages students to make connections among energy concepts in photosynthesis. While working on the inquiry unit, students in the dynamic condition interacted with a dynamic visualization of energy transformation, whereas students in the static condition interacted with a series of static illustrations of the same concept. The results showed that students in both conditions added new, scientific ideas about energy transformation and developed a more coherent understanding of energy in photosynthesis. However, when comparing the two conditions, we found a significant advantage of dynamic visualization over static illustrations. Students in the dynamic condition were significantly more successful in articulating the process of energy transformation in the context of chemical reactions during photosynthesis. Students in the dynamic condition also demonstrated a more integrated understanding of energy in photosynthesis by linking their ideas about energy transformation to other energy ideas and observable phenomena of photosynthesis than those students in the static condition. This study, consistent with other research, shows that dynamic visualizations can more effectively improve students' understanding of abstract concepts of molecular processes than static illustrations. The results of this study also suggest that with appropriate instructional support, such as making predictions and distinguishing among ideas, both dynamic visualizations and static illustrations can benefit students. This study underscores the importance of curriculum design in ensuring that dynamic visualizations add value to science instructional materials. © 2012 Wiley Periodicals, Inc. J Res Sci Teach 49: 218–243, 2012

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Dynamic visualizations can potentially improve students' understanding of abstract scientific phenomena, such as photosynthesis and chemical reactions, by animating unseen processes (Cook, 2006; Fleming, Hart, & Savage, 2000; Kelly & Jones, 2007; Rotbain, Marbach-Ad, & Stavy, 2006; Williamson & Abraham, 1995). Yet the effects of dynamic visualizations on students' learning are controversial. Some studies report that dynamic visualizations are superior to static illustrations, while others report the reverse (Höffler & Leutner, 2007; Tversky, Bauer-Morrison, & Betrancourt, 2002). A wide range of complex factors contribute to the

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impact of dynamic visualizations, such as duration of instruction, use of instructional support to facilitate learning (e.g., prediction and reflection), and types of scientific concepts being portrayed (e.g., microscopic vs. observable changes) (Hegarty, 2004; Tversky et al., 2002). Thus, the important question is, when and how do dynamic visualizations add value to students' understanding of abstract scientific concepts?

In this study, we investigated the value of dynamic visualizations, as compared to static illustrations, for promoting middle school students' integrated understanding of energy in photosynthesis. We designed two versions of a web-based inquiry unit focused on energy transformation in photosynthesis and created a dynamic visualization and static illustrations of the relevant molecular interactions during energy transformation. We compared the impact of the two versions to answer the following questions:

- How do dynamic visualizations, compared to static illustrations, improve middle school students' understanding of energy transformation in photosynthesis?
- How do dynamic visualizations, compared to static illustrations, help middle school students make connections between energy transformation at the molecular level and other energy ideas in photosynthesis?

Dynamic Visualizations and Static Illustrations for Science Learning

Dynamic visualizations have the potential to make abstract scientific concepts, such as molecular processes, more accessible to students. They can provide detailed representations of unobservable scientific phenomena (Ardac & Akaygun, 2004, 2005; Kozma & Russell, 1997; Sanger, Brechelsen, & Hynek, 2001; Stieff, 2011; Tasker & Dalton, 2006). They can also animate dynamic changes in scientific processes that are difficult to infer from static illustrations found in textbooks (Lewalter, 2003; Marbach-Ad, Rotbain, & Stavy, 2008; Sanger et al., 2001; Williamson & Abraham, 1995). Indeed, several studies suggest that dynamic visualizations of chemical reactions are more effective than static illustrations in helping students develop a coherent understanding of abstract molecular changes. For example, Ardac and Akaygun (2005) found the advantage of their dynamic visualizations over static illustrations in teaching 8th-grade students the concept of chemical changes at the molecular level. Similarly, Yarden and Yarden (2010) also reported that the dynamic motions used in animations can enable 10th-grade students to develop a stronger mental model of molecular processes, compared to static visuals. These examples show that dynamic visualizations can help students understand dynamic molecular processes better than static illustrations by providing a more accurate illustration of how molecules interact with each other during chemical reactions.

Despite the potential benefits of dynamic visualizations, they are not always more effective than static illustrations (Höffler & Leutner, 2007; Kali & Linn, 2008; Lowe, 2003; Mayer, Hegarty, Mayer, & Campbell, 2005; Tversky et al., 2002). For example, Tversky et al. (2002) found that there was no distinctive advantage of using dynamic visualizations over static illustrations in the studies they reviewed. Mayer et al. (2005) also found that static diagrams can be more effective in improving learners' understanding of the physical and mechanical systems than narrated animations. By contrast, Höffler and Leutner (2007) found a small overall benefit for dynamic visualizations compared to static illustrations in their meta-analysis of 26 studies that compared dynamic visualizations to static depiction. These contradictory findings reflect many factors including whether the visualization portrays unobservable (microscopic) or observable phenomena and whether outcome measures are aligned with instruction (e.g., retention vs. integrated understanding) (Hegarty, 2004; Höffler & Leutner, 2007; Tversky et al., 2002).

Some studies suggest that positive outcomes for dynamic visualizations over static illustrations might be due to additional information or instructional support provided in the dynamic visualizations. Tversky et al. (2002) found that in some studies, dynamic visualizations provided more information about the content being taught than static illustrations. In other studies, dynamic visualizations allowed interactivity (e.g., Schnotz & Grzondziel, 1999) or provided prediction questions (e.g., Hegarty, Quilici, Narayanan, Holmquist, & Moreno, 1999), both of which could facilitate learning but were not available in the static illustrations.

Efforts to make dynamic visualizations and static illustrations as comparable as possible have resulted in mixed findings. Even when dynamic visualizations and static illustrations were comparable, some studies found that dynamic visualizations did not provide additional benefits compared to static illustrations (Morrison & Tversky, 2001; Rieber, 1989). Because dynamic visualizations rapidly present complex information about abstract scientific concepts, they may confuse students or distract students from focusing on relevant information (Lewalter, 2003; Lowe, 2003; Mayer & Gallini, 1990; Mayer & Moreno, 2003; Pass, Renkl, & Sweller, 2003; Rieber, 1989). In particular, several studies show that students with low prior knowledge often find dynamic visualizations that illustrate complex scientific processes difficult to comprehend (Cook, 2006; Lowe, 2003; Yarden & Yarden, 2010).

Another explanation for the failure of dynamic visualizations to support students' learning is that dynamic visualizations can be deceptively clear (Chiu, 2010; Linn, Chang, Chiu, Zhang, & McElhaney, 2010; Linn & Eylon, 2011). Students may overestimate their comprehension of scientific concepts presented in dynamic visualizations after initial viewing and fail to explore the visualizations in depth (Chiu, 2010; Linn & Eylon, 2011). For example, in Chiu's study (2010), high school students who viewed a visualization of chemical reactions had greater confidence in their understanding before they were asked to explain the phenomena than after they gave an explanation. Vermaat, Terlouw, and Dijkstra (2003) found that 10th-grade students who watched an animation of phase changes in water molecules stated that they liked the animation but most of them were unable to use the information from the animation to explain their understanding of chemistry at the symbolic, molecular, and macroscopic levels. This deceptive clarity of dynamic visualizations can create additional misconceptions, rather than support student learning (Betrancourt, 2005; Kali & Linn, 2008; Lewalter, 2003; Linn et al., 2010; Linn & Eylon, 2011).

As research shows, we need a more nuanced understanding of how dynamic visualizations and static illustrations contribute to students' integrated understanding of science. This requires us to develop a clearer sense of how to design instruction to take advantage of dynamic visualizations and to better understand the conditions that lead to benefits from dynamic visualizations compared to static illustrations.

To advance our understanding about the benefits of dynamic visualizations and static illustrations in science teaching and learning, we designed two versions of a web-based inquiry unit on photosynthesis and conducted a comparison study that varied the format of instruction on energy transformations in photosynthesis. The first version of the inquiry unit used a dynamic visualization of the process of energy transformation, whereas the second version presented the same information using static illustrations. To design the comparisons, we used methods from prior research (Kehoe, Stasko, & Taylor, 2001; Mayer et al., 2005) and created a static version of the visualization that captures the central ideas of energy transformation in the dynamic visualization. Except for the movement of molecules, both dynamic and static conditions were identical. We compared the impact of the two versions on middle school students' integrated understanding of energy in photosynthesis. We specifically explored how students used the information in each version of the unit to understand energy transformation and to make meaningful connections between energy transformation and other energy concepts in photosynthesis.

Energy Transformation in Photosynthesis

Energy transformation, the process of energy being changed from one form to another, is a key concept in photosynthesis (American Association for the Advancement of Science [AAAS], 1993, 2005; National Research Council, 1996). To fully understand photosynthesis, students must integrate the relationships between energy transformation and observable aspects of plant growth (Kesidou & Roseman, 2002; Stern & Roseman, 2004). Yet, understanding energy transformation is challenging for middle school students for two reasons. First, the process of how light energy is transformed into chemical energy during photosynthesis is abstract and unobservable (Roseman, Stern, & Koppal, 2010). Second, energy transformation involves chemical reactions between carbon dioxide and water molecules that require light energy. This requires students to understand that light energy provides the activation energy for the reaction between carbon dioxide and water molecules. Essentially, light energy is used to break the bonds of these molecules initiating a reaction that results in energy transformation. These chemistry concepts are new to middle school students. This study explores ways to make the abstract process of energy transformation more explicit to students by comparing dynamic visualizations and static illustrations.

Despite its importance in understanding photosynthesis, research shows that energy transformation during photosynthesis is often only vaguely articulated in middle school science curriculum materials. Kesidou and Roseman (2002) examined nine sets of middle school science curricular materials and found that most materials discussed photosynthesis in terms of reactants and products without explaining the process of energy transformation. Stern and Roseman (2004) also reported that most science curricula in life science emphasized the importance of light energy in photosynthesis but rarely discussed how light energy is converted into chemical energy and how it is stored as a form of sugar. Even the few materials that do introduce the transformation of energy during photosynthesis present the chemical equation of photosynthesis without an introduction to chemical changes between atoms and molecules (Stern & Roseman, 2004).

For example, the following excerpt from a 7th-grade science textbook (Coolidge-Stolz et al., 2008) provides only a high level description and a chemical formula to help students understand how light energy is used to start chemical reactions and how dynamic, abstract molecular changes ensue:

> Inside the chloroplasts, the water and carbon dioxide undergo a complex series of chemical reactions. The reactions are powered by the energy captured in the first stage. These reactions produce chemicals as products. One product is a sugar that has six carbon atoms. Six-carbon sugars have the chemical formula $C_6H_{12}O_6$ . . . The other product of photosynthesis is oxygen (O_2), which exits the leaf through the stomata (p.121).
>
> $$\underset{\text{carbon dioxide}}{6CO_2} + \underset{\text{water}}{6H_2O} \xrightarrow{\text{light energy}} \underset{\text{a sugar}}{C_6H_{12}O_6} + \underset{\text{oxygen}}{6O_2}$$
>
> Notice that the raw materials—six molecules of carbon dioxide and six molecules of water—are on the left side of the equation. The products—one molecule of a sugar and

> six molecules of oxygen—are on the right side of the equation . . . Light energy, which is necessary for the chemical reaction to occur, is written above the arrow (p.122).

This type of instruction can mislead students into believing that light energy disappears or is destroyed and plants create glucose out of nothing instead of through the rearrangement of carbon dioxide and water during photosynthesis (Mohan, Chen, & Anderson, 2009; Stern & Roseman, 2004). The lack of explicit representations of energy transformation can also result in students' inability to make connections between energy ideas across different topics in life science, such as cellular respiration and ecosystems (Kesidou & Roseman, 2002; Köse, 2008; Nordine, Krajcik, & Fortus, 2011; Stern & Roseman, 2004). For example, when textbooks introduce the concept that plants release energy from glucose during cellular respiration, students need to link this information back to energy transformation in photosynthesis and understand that the energy originally comes from the sun. Without an integrated understanding of energy transformation in photosynthesis, students are not able to build on their knowledge of energy and comprehend how energy flows in an ecosystem. When students encounter chemical reactions in high school, they are not prepared by their middle school texts to extend their understanding to the more sophisticated view of energy transformation necessary for advanced topics (Kesidou & Roseman, 2002; Stern & Roseman, 2004).

Besides the views that light energy disappears and plants create a new substance, many students hold a wide range of alternative ideas about photosynthesis. Students often believe that plants get their food from soil (Anderson, Sheldon, & Dubay, 1990; Barker & Carr, 1989; Çepni, Tas, & Köse, 2006; Eisen & Stavy, 1988; Roth, Smith, & Anderson, 1983; Wood-Robinson, 1991). Some students think that water is the source of energy for plants (Çepni et al., 2006) or that oxygen is one of the main elements for photosynthesis (Marmaroti & Galanopoulou, 2006; Stavy, Eisen, & Yaakobi, 1987). Students also express inaccurate ideas about different forms of energy, such as energy being one of the substances that plants absorb during photosynthesis (Stavy et al., 1987). Students are also confused about whether plants need heat energy or light energy for photosynthesis (Carlsson, 2002; Marmaroti & Galanopoulou, 2006). Furthermore, most students have difficulties understanding how light energy is converted into chemical energy during photosynthesis (Anderson, 1986; Arnold & Simpson, 1980; Eisen & Stavy, 1988; Hesse & Anderson, 1992; Johnson, 2000; Marmaroti & Galanopoulou, 2006; Waheed & Lucas, 1992). Wilson et al. (2006) report that even some college students fail to accurately trace energy in photosynthesis and cellular respiration.

This extensive range of alternative ideas about photosynthesis reflects the lack of emphasis on energy transformation during photosynthesis in most science courses. Because energy transformation during photosynthesis is often oversimplified and abstract in the curriculum, students may draw on their observations and conjectures (Linn & Hsi, 2000). To improve students' coherent understanding of energy transformation during photosynthesis, it is important to explicitly represent how light energy is used to start chemical reactions and how light energy is transformed into chemical energy inside the chloroplast.

Only a few studies investigate the role of visualizations in improving students' understanding of energy in photosynthesis. For instance, Höffler, Prechtl, and Nerdel (2010) investigated the impact of visual cognitive style on middle school students' understanding of chemical reactions during photosynthesis using dynamic visualizations and static pictures. Their findings indicated no significant benefits of animations over static pictures for either highly or less visual learners. Huk, Steinke, and Floto (2010) investigated the effects of 3D visualizations and visual cues in promoting college students' understanding of the enzyme ATP-synthase in a controlled laboratory setting and a classroom setting. They found that 2D or 3D representations in the visualizations did not have a significant impact on student learning in the classroom setting, but the use of visual cues significantly helped students recall what they learned in the visualizations. In this study, we compared dynamic visualizations to static illustrations to explore ways to make the process of energy transformation in the context of chemical reactions more accessible and understandable for middle school students.

Visualizing Energy Transformation in Photosynthesis Using Knowledge Integration

Both dynamic visualizations and static illustrations can help students add valuable ideas about abstract scientific phenomena to their repertoire of ideas. However, simply presenting new information using visual representations does not automatically enable students to use the information to develop an integrated understanding of the concepts. Research shows that students benefit from additional instructional support to distinguish new ideas presented in the visualizations from their existing ideas (Kali & Linn, 2008; Linn & Eylon, 2011; Quintana et al., 2004). In this study, we used the Web-based Inquiry Science Environment (WISE) and design principles from the knowledge integration framework to design inquiry instruction (Slotta & Linn, 2009). We embedded the dynamic and static versions of the visualizations in a WISE unit designed to improve middle school students' understanding of energy in photosynthesis.

Knowledge Integration Framework

Knowledge integration is an instructional framework that emphasizes the process by which students gradually make elaborated connections between normative scientific ideas and their repertoire of existing ideas and eventually develop a coherent, integrated understanding of complex scientific concepts (Linn & Eylon, 2011). The framework identifies four processes that jointly promote integrated understanding: *eliciting ideas*, *adding ideas*, *distinguishing ideas*, and *sorting out ideas*.

First, knowledge integration emphasizes *eliciting and building on a repertoire of ideas* students have developed about scientific phenomena from their experiences and observations. Eliciting ideas involves asking students to generate ideas about a specific scientific topic to ensure that instruction deals with all of their views. The photosynthesis unit used in this study elicits students' repertoire of ideas about energy in photosynthesis by asking students to generate ideas about what would have happened to the dinosaurs had there been no sun on earth.

Second, knowledge integration, like most instructional frameworks, emphasizes *adding new, normative ideas* about scientific phenomena to students' repertoire of ideas. In this study, students add new ideas about how light energy is transformed into chemical energy during photosynthesis using dynamic visualizations and static illustrations. Students also add new ideas about the relationship between light energy and glucose production by manipulating variables and conducting their own experiments using virtual experiments.

Third, knowledge integration emphasizes providing guidance to help students *develop criteria to distinguish new ideas from existing ideas*. When students only add ideas they often end up with isolated or confusing ideas that are disconnected from their existing ideas (Linn & Eylon, 2011; Linn & Hsi, 2000). In time they may revert to their original ideas. Students need multiple opportunities to link new ideas to their repertoire of ideas and to develop criteria to distinguish among these ideas. For example, students might make predictions based on their existing ideas and then compare their predictions to their observations of the visualization. By comparing their existing ideas to the new ideas and examining how these ideas are connected or different students can make sense of the new information. Distinguishing ideas can also help students overcome the possible deceptive clarity of visualizations (Linn et al., 2010). To distinguish ideas in this study, students critique the work of their peers using the evidence from the visualization to determine which ideas are scientifically valid. They also compare their predictions to their observations and analyze the differences.

Finally, knowledge integration emphasizes *sorting out ideas* to make meaningful links among ideas and develop a more integrated understanding of scientific phenomena. Sorting out ideas involves asking students to reflect on evidence collected from visualizations, organize their ideas, and connect and synthesize them in a coherent way. This process helps students identify gaps or misconnections in their understanding and refine their ideas. In this study, students were asked to connect ideas about energy concepts by writing explanatory narratives to show how energy is involved in photosynthesis.

WISE Photosynthesis Unit

To help students develop an integrated understanding of the role of energy in photosynthesis, we designed a WISE photosynthesis inquiry unit using knowledge integration processes. We used a partnership design approach involving a team of educational researchers, middle school science teachers, technology developers, and content experts who collaborated to design inquiry activities and associated technology to support students' learning. This inquiry unit was implemented using WISE, an open-source learning environment, to deliver online instruction and log students' responses (see Slotta & Linn, 2009). Consistent with the California science standards, this project features three inquiry activities focused on energy sources, energy transformation, energy storage, and energy transfer in photosynthesis to help students develop an integrated understanding of energy in photosynthesis. Key concepts addressed in each activity, specific learning goals, and learning tasks are presented in Table 1.

The first activity introduces observable aspects of photosynthesis starting with the sun as the original energy source for plants in a series of visualizations. Students also explore unobservable phenomena in visualizations that illustrate how plants produce glucose and oxygen by using carbon dioxide, water, and light energy from the sun. The activity also challenges students' misconceptions about soil as one of the reactants of photosynthesis.

The second activity emphasizes how light energy is converted into chemical energy and stored in glucose using dynamic visualizations. The visualizations in this activity "zoom" into the plants and introduce the roles that chloroplasts and chlorophyll play in photosynthesis. In this activity, visualizations then show how light energy is used to break up carbon dioxide and water molecules which are recombined to create glucose and oxygen molecules, and how energy is transformed and stored inside glucose. Students in the dynamic condition interact with a dynamic visualization of energy transformation, while students in the static condition interact with a series of static illustrations of the same concept. In this activity, students also have an opportunity to use virtual experiments to explore how the amounts of light, carbon dioxide, and water affect the production of glucose in the chloroplast.

The third activity enables students to use virtual experiments to explore how plants use the glucose created in the chloroplast and how energy is transferred from the plant to animals. For example, students grow virtual plants for 10 weeks by manipulating the amount of light. Following their investigations, students draw conclusions about how light energy can affect plant growth. In this activity, students also have an opportunity to integrate their understanding of energy transformation in photosynthesis by creating a diagram about the flow of energy using a computer-based diagramming environment called MySystem (see Figure 1).

Table 1
Energy concepts, learning goals, and learning task

Sequence	Energy Concept	Learning Goals	Learning Task
Activity 1: Where Does Energy Come From?	Energy source	Students will learn to explain the sun as the main source of energy identify that the sun gives off light energy explain that plants use light energy from the sun, water, and carbon dioxide to create glucose and oxygen correctly label where the water, sunlight, and carbon dioxide enter the plant describe why animals need plants, such as oxygen and energy in glucose	Students interact with visualizations that illustrate the observable aspects of photosynthesis Students take an interactive quiz about what plants need for photosynthesis Students interact with visualizations that show how plants use glucose and how plants take in carbon dioxide and release oxygen Students watch a short clip about hydroponics and discuss whether plants need soil to grow
Activity 2: How Is Energy Transformed?	Energy Transformation Energy Storage	Students will learn to describe photosynthesis as a chemical reaction involving molecules differentiate between the structure and function of chloroplasts and chlorophyll illustrate how light energy is converted into chemical energy in the chloroplast distinguish between light and chemical energy explain that chemical energy is stored in glucose make hypotheses, run experiments, and explain results	Students distinguish differences between chlorophyll and chloroplast and link them to photosynthesis by interacting with visualizations Students interact with visualizations of energy transformation at the molecular level and explain the role of energy in creating glucose Students make predictions; manipulate the levels of light energy, carbon dioxide, and water; and test their hypotheses to explore how light energy, carbon dioxide, and water affect the glucose production in the chloroplast
Activity 3: Where Does Energy Go?	Energy Transfer	Students will learn to explain how plants use energy from glucose to grow and survive explain that energy in glucose is transferred to animals when they eat the plants use a computer model to test variables in growing plants with light energy, water, dissolved minerals, and soil make hypotheses, run experiments, and explain results	Students conduct virtual experiments to investigate how the amount of light energy affects the plant growth Students make hypotheses, conduct their own experiments, and draw conclusions from their results Students view the energy pyramid diagram that illustrates how energy transfers and is lost Students write an Energy Story and generate a MySystem diagram to show how energy flows from the Sun to the rabbit

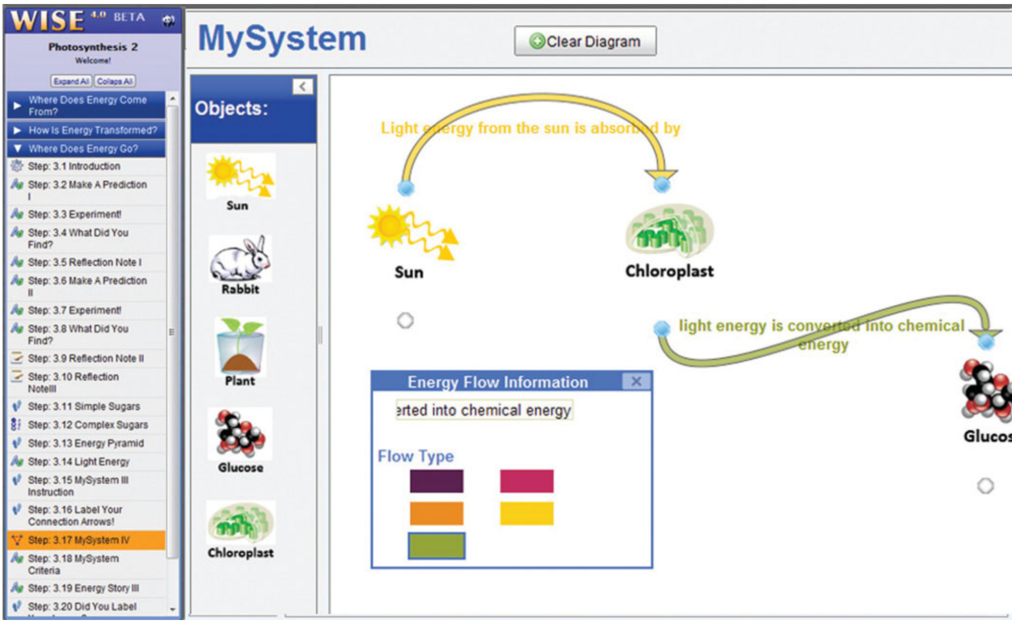

Figure 1. The Web-based Inquiry Science Environment, showing the interface of a MySystem diagram tool.

MySystem allows students to represent the flow of energy by connecting icons with arrows and annotating each relationship between energy concepts, such as energy transformation. Using MySystem, students visualize how light energy is transformed in the chloroplast, how chemical energy is stored in glucose, and how energy moves from the plant to other animals. During this process, students can integrate energy ideas they learned from the instruction and refine their understanding of energy in photosynthesis.

Designing a Dynamic Visualization and Static Illustrations of Energy Transformation Using Knowledge Integration

To make abstract concepts of energy transformation visible to students, we created and embedded a dynamic visualization (dynamic condition) and static illustrations (static condition) of energy transformation at the molecular level in the inquiry instruction. To focus instruction on integrated understanding of energy transformation during photosynthesis, we implemented the knowledge integration framework. Using the knowledge integration framework, we carefully designed the dynamic visualization and static illustrations to not only add new ideas to students' repertoire of concepts, but also to provide opportunities for them to sort out their ideas and integrate them into their existing knowledge (Kali & Linn, 2008).

Before students interact with the visual materials, we *elicit students' repertoire of ideas* about energy transformation by asking students to predict what light energy would do to carbon dioxide and water molecules to create glucose molecules (prediction question). Students then *add new ideas* about the process of energy transformation by interacting with either the dynamic visualization (http://wise.berkeley.edu/upload/37466/ET_Dynamic.html) or static illustrations (http://wise.berkeley.edu/upload/37466/ET_Static.html). The dynamic visualization sequentially illustrates dynamic processes of energy transformation at the molecular level in segments (Figure 2). The dynamic visualization starts with how light energy,

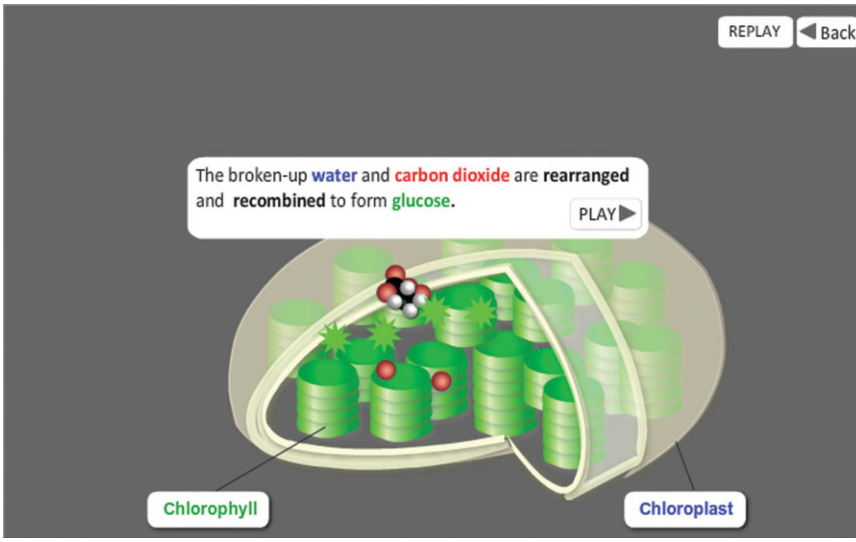

Figure 2. A screenshot of the dynamic visualization of energy transformation.

carbon dioxide and water enter the chloroplast. Then it shows how light energy starts chemical reactions by breaking carbon dioxide and water molecules which are later rearranged to form glucose and oxygen. Simultaneously the visualization shows how light energy is converted into chemical energy during this process and stored inside glucose molecules. The dynamic condition animated continuous changes of how molecules interact with each other and how energy changes from one form to another.

To create the static condition, we captured the key phenomena of energy transformation shown in the dynamic visualization. The static condition involved a sequence of 15 snapshots of changes directly captured from the dynamic condition. Both the dynamic and static conditions provide written explanations coordinated with the instruction. In both conditions, students could also interact with the materials and control their pace by clicking a back button or a next button and replay the images and instructions as frequently as they wished. Except for the movements between atoms and molecules, both dynamic and static conditions were identical in terms of content, graphics, and interactivity. This technique is similar to the approach taken by other researchers (Kehoe et al., 2001; Mayer et al., 2005).

Students then have opportunities to *distinguish and sort out ideas* by comparing their predictions from the visualization and reflecting on their ideas about energy transformation using the information given in the visualization. Immediately after interacting with the visualization or illustrations, students were asked to distinguish between the information in the visualizations and their existing ideas. They explained how light energy interacts with carbon dioxide and water molecules to create glucose molecules (reflection question). This process can overcome the potential deceptive clarity of the visualization by guiding students to distinguish their expectations from their observations (Linn et al., 2010; Linn & Eylon, 2011). At the end of the project, students were asked to reflect on the concept of energy transformation and explain the role of light energy in photosynthesis by linking their understanding of energy transformation to other energy ideas in photosynthesis (delayed reflection question). This knowledge integration process can lead to a coherent, integrated understanding of the complex processes of energy transformation at the molecular level during photosynthesis.

Methods

Participants and Study Design

Two hundred 7th-grade students from nine classes at a Bay Area middle school participated in this study. All 200 students completed the photosynthesis unit, but only 167 students finished both pre- and posttests. Thirty-three students who missed either the pretest or the posttest were excluded from the pre-posttests analysis. Students were taught by two science teachers who had 5 years of experience integrating technology into their science teaching. Students in each class were randomly assigned to either the *dynamic* (dynamic visualization of energy transformation) or *static* (static illustrations of energy transformation) condition and worked on the photosynthesis inquiry project in pairs for 12 days (Figure 3). Most students

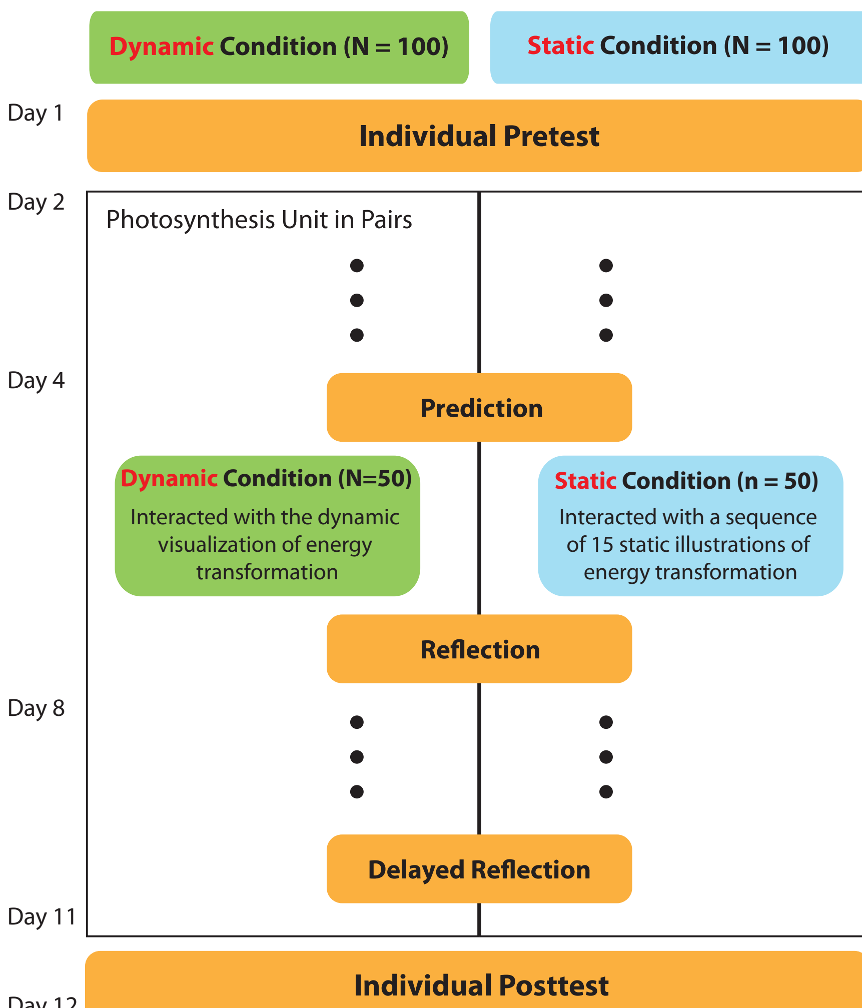

Figure 3. Study design.

had prior experience with technology-enhanced science projects. Students had not received any formal instruction about photosynthesis prior to the study.

Procedures and Classroom Observations

Before the study began, all students spent one class period to individually complete an online pretest designed to assess their integrated understanding of energy concepts in photosynthesis. After completing the pretest, students in each class were randomly assigned to either the dynamic or static condition and started the photosynthesis inquiry unit in pairs for 10 days. Students in the dynamic condition completed the first version of the inquiry unit using the dynamic visualization that shows dynamic processes of how light energy is transformed into chemical energy in the context of chemical reactions during photosynthesis. Students in the static condition completed the second version of the unit using static illustrations which had identical content and illustrations but lacked dynamic movements of molecules.

Both versions had identical embedded assessments designed to measure students' understanding of key phenomena in energy transformation (Table 2). Prior to interacting with the visualizations, students were asked to predict what light energy would do to carbon dioxide and water molecules. Immediately following the visualizations, students were asked to answer to the same question using the evidence collected from the visualizations. At the end of the photosynthesis inquiry unit, students were asked to reflect on what they learned from the visualization and explain the role of light energy in creating glucose. Overall students in both the dynamic and static conditions spent a similar amount of time to complete the project.

During class, the teachers walked around the classroom to provide guidance and answer questions related to technical or project-related issues. When the teachers noticed students' difficulties with new visualizations, such as a virtual experiment simulation, they stopped the class and introduced main variables that students would manipulate for their experiments. After completing the unit, students responded individually to an online posttest for 1 day. Pre- and posttests were identical to each other.

The first author was present for every class. She answered technical questions about the visualizations or networking. She took notes on classroom activities primarily to document fidelity of implementation and to ensure that classes were all treated similarly.

Knowledge Integration Assessment

Students' integrated understanding of energy in photosynthesis was measured using pre- and posttests. The pre- and posttests included five items, aligned with the instruction, which asked students to connect their ideas about energy transformation to other energy concepts in photosynthesis (Table 3). These assessments were designed to measure how

Table 2
Embedded Assessments

Item		Description
Prediction	Prior to the visualization	What does light energy do to carbon dioxide and water molecules to create glucose molecules?
Reflection	Immediately following the visualization	What does light energy do to carbon dioxide and water molecules to create glucose molecules?
Delayed Reflection	At the end of the curriculum (in Activity 3)	What is the role of light energy in creating glucose?

Table 3
Pretest and posttest items

Item	Energy Concept	Description
Tree Item	Energy source Energy transformation	Asks students to select a pair that represents sunlight energy being converted into chemical energy and explain how this process happens in the selected pair
Chloroplast Item	Energy source Energy transformation Energy storage	Asks students to select an accurate explanation about the main function of chloroplast and explain their choice
MySystem Critique	Energy source Energy transformation Energy storage	Asks students to critique the ill-structured, pre-made visual representation of energy flow in photosynthesis and change the arrow and label of energy transformation
Sun Item	Energy source Energy transformation Energy storage Energy transfer	Asks students to explain how sun helps animals survive
Energy Stories	Energy source Energy transformation Energy storage Energy transfer	Asks students to provide explanatory narratives about how plants use energy to grow by linking energy source, energy transformation, energy storage, and energy transfer concepts

students make connections between ideas about energy concepts related to photosynthesis, rather than isolated facts about reactants and products of photosynthesis (Liu, Lee, Hofstetter, & Linn, 2008).

Each question was scored using a specific knowledge integration rubric that was designed based on students' normative ideas and elaborated links between these ideas related to the item content (Linn, Lee, Tinker, Husic, & Chiu, 2006). The knowledge integration rubric consists of five levels of reasoning (Table 4). Higher scores indicate that students identified more scientifically elaborated links between energy ideas and coherently integrated them in their responses. The possible maximum score of each item was 5, and a minimum score was 1.

Results and Discussion

To investigate the benefits of dynamic visualizations versus static illustrations of energy transformation in photosynthesis, we compared the impact of two versions of a WISE unit on middle school students' integrated understanding of photosynthesis. Students in nine 7th-grade classrooms were randomly assigned to the dynamic or static condition and completed instructional activities over 12 days. The dynamic and static conditions differed only in the animation of molecular movements during energy transformation (presented in Activity 2). During the project, the participating teachers monitored students' progress and provided guidance to help students complete the project. The teachers interrupted the class to lead a group discussion only when they noticed students were confused by specific scientific concepts. Notes taken by the first author documented that interruptions were similar across classes and that students appeared to be engaged in the project, particularly in exploring the visualizations.

Table 4
Knowledge integration rubric

Score	KI Level	Description	Sample Student Responses From the Sun Item
1	Off-task	No answer or off-task	"I don't know"
2	No Link	Non-normative or scientifically invalid links and ideas	"The sun helps animals survive by making heating the soil and making food for them" "The sun helps animals survive by growing food for them"
3	Partial Link	Normative ideas without scientifically valid connections between ideas	"The sun helps the animals survive because the plants need the sun and animals eats plants and if those animals don't get those plants those animals die and the animals that eat the animals don't get there food, and plus without the sun everything would die"
4	Full Link	One scientifically valid and elaborated link between normative and relevant energy ideas	"When the sun is absorbed by the chloroplast in a plant's leaves, the chloroplast then produces glucose and oxygen so the animals can eat and breathe" "The sun helps plants stay alive because it gives plants energy for photosynthesis. Then the animals eat the plants and get energy from the plants. If the sun didn't keep the plants alive animals wouldn't be alive because there would be no plants to keep them alive"
5	Complex Link	Two or more scientifically valid and elaborated links between normative and relevant energy ideas	"The sun helps animals survive by giving light energy to plants. Light energy is needed in photosynthesis. Plants can take the process of photosynthesis to result in glucose. Glucose is sugar that helps the plant grow. So when an animal eats a plant the energy is transferred to the animal. The energy helps make the animal live" "The sun helps animals survive by provided healthy plants for them to eat. When the sun is absorbed by the chloroplast in the leaves of the plant it changes the energy into glucose this is called photosynthesis. Animals eat the plant so they receive the energy from the plant which originally came from the sun"

Students' Understanding of the Process of Energy Transformation: Embedded Assessments

Prior Knowledge. To establish that students' understanding of energy transformation was similar across conditions, we compared students' performance on the prediction question embedded in the project. Prior to using the visualizations of energy transformation, there were no significant differences between students in the dynamic and static conditions in terms of their understanding of what light energy would do to carbon dioxide and water to create glucose during photosynthesis [$t(98) = 0.36$, $p = 0.72$]. Most students in both conditions started with a wide range of scientifically invalid ideas about the role of light energy in photosynthesis. For example, many students predicted that "light energy pushes carbon dioxide and water out of the chloroplast as glucose" or that "light energy absorbs carbon dioxide and water in the chloroplast." None of the students mentioned how light energy is involved in starting chemical reactions or how light energy is transformed into chemical energy.

Embedded Assessment Trajectories. To assess how the dynamic and static conditions helped students add new ideas about energy transformation and distinguish them from their existing ideas, we tracked responses and compared student performance across the embedded assessment items: prediction (prior to the visualizations), reflection (immediately after the visualizations), and delayed reflection (at the end of the instruction).

The ANOVA results revealed that after interacting with visual materials, students in both the dynamic and static conditions showed significant improvement in understanding energy transformation at the molecular level (Table 5). For both groups, performance on the reflection was significantly higher than on the prediction item with large effect sizes (Cohen, 1988). Students in both conditions started with non-normative ideas about energy transformation, but they successfully added new ideas about how light energy is converted into chemical energy and how chemical reactions occur during this process. The large effect sizes for the differences between their prediction and reflection items clearly show that students were able to reflect on gaps in their understanding and successfully refine their ideas. For both conditions, mean scores of the delayed reflection question slightly decreased. Nevertheless, students in both conditions maintained improved understanding of energy transformation and were able to explain the role of light energy in creating glucose during photosynthesis. These findings indicate that with appropriate instructional support, both the dynamic visualization and static illustrations were effective in helping middle school students understand the abstract concept of energy transformation at the molecular level.

Effects of the Dynamic and Static Conditions. Although students in both conditions improved between the prediction and the two reflection questions, students in the dynamic condition significantly outperformed students in the static condition on both immediate reflection items with a large effect size of 0.86 [$t(98) = 3.58$, $p < 0.01$] and delayed reflection items with a medium to large effect size of 0.79 [$t(98) = 3.88$, $p < 0.001$].

In the dynamic condition, 90% of the students successfully distinguished new ideas presented in the visualization from their existing ideas and accurately explained the process of energy transformation by making at least one scientifically valid link on the immediate reflection question. Students in the dynamic condition accurately explained that light energy is used to start chemical reactions and indicated that the reaction involves breaking up molecules and forming glucose. They also indicated that light energy is transformed into chemical energy during this process. For example, one pair in the dynamic condition said, "Light

Table 5
Average knowledge integration scores and standard deviations for the embedded prediction, reflection, and delayed reflection questions

N (Pair)	Prediction (SD)	Reflection (SD)	Delayed Reflection (SD)	*F*	Paired Comparisons
Dynamic Condition					
50	2.52 (0.75)	4.59 (0.58)	4.00 (0.82)	115.83[a]	Prediction/Reflection[a] ($d = 3.09$) Prediction/Delayed reflection[a] ($d = 1.88$)
Static Condition					
50	2.54 (0.93)	3.88 (1.02)	3.34 (0.85)	30.70[a]	Prediction/Reflection[a] ($d = 1.38$) Prediction/Delayed reflection[b] ($d = 0.90$)

[a]$p < .001$.
[b]$p < .01$.

energy, carbon dioxide molecules, and water molecules enter the Chloroplast. Light energy hits carbon dioxide and water molecules and separates them . . . the Chloroplast recombines the molecules to form glucose. Glucose is a form of chemical energy that plants use to grow. In addition, the plant releases oxygen as a waste product.''[1]

In the static condition only 62% of the students accurately articulated the molecular processes during which energy transformation occurs on the immediate reflection question. Twenty-eight percent of students in the static condition provided scientifically normative ideas about energy transformation but did not make connections between their ideas. In addition, 10% of the students in the static condition developed a new alternative idea that ''carbon dioxide and water molecules are absorbed by the chloroplast'' after they are split up. This newly developed misconception indicates that static illustrations may reinforce the belief that chemical reactions occur instantaneously, rather than that they involve bond breaking and bond formation.

On the delayed reflection item, students in the dynamic condition, compared to students in the static condition, were significantly more successful in retaining their coherent understanding of energy transformation with at least one elaborated link (Table 5). Students in the dynamic condition were significantly better able to articulate the detailed process of how light energy starts chemical reactions and how molecules react with each other than their counterparts in the static condition. This finding clearly shows that without detailed insights into the dynamic processes of energy transformation, it is difficult for middle school students to understand how plants convert the three reactants into two completely different substances. Consistent with previous research (Ardac & Akaygun, 2005; Jones, Jordon, & Stillings, 2001; Sanger, Phelps, & Fienhold, 2000; Williamson & Abraham, 1995; Zhang & Linn, 2011), the results suggest that the dynamic visualizations have a significant advantage over static illustrations when teaching the complex, dynamic process of chemical reactions.

Linking Energy Transformation Ideas to Photosynthesis: Individual Pre- and Posttests

Prior Knowledge. To ensure that both conditions were equivalent before the study in their ability to link ideas about energy transformation to other related energy concepts in photosynthesis, we compared the two groups' pretest scores. The results revealed no significant difference between the static and dynamic conditions [$t(165) = 0.67$, $p = 0.51$], indicating that before the study, students in both conditions had similar abilities to make connections between energy ideas in photosynthesis (Table 6). Note that students who missed either the pretest or the posttest were omitted from this analysis. Omitted students in the static and dynamic conditions who took the pretest performed similarly to each other.

The analysis of students' pretest scores confirmed that students in both conditions started with irrelevant and non-normative ideas about energy transformation. These student responses illustrate the range of ideas students gain from everyday experience, consistent with the knowledge integration view (Linn & Eylon, 2011). Many students explained that ''plants need energy from the sun,'' reflecting their observations that plants grow in summer or in sunny weather, but they did not distinguish heat energy from light energy in photosynthesis. Students also argued that ''plants get energy from the soil'' or that ''energy ends up in the soil,'' consistent with observations that roots connect the plant to the soil. A few students mentioned the general idea that energy is transformed during photosynthesis. These students generally had incomplete ideas about this process, such as ''energy is transformed into photosynthesis'' or ''energy is transformed into a living organism.''

Table 6
Average knowledge integration scores, standard deviations, and effect sizes for the pre- and posttest

Item	Knowledge Integration Score		t	Cohen's d
	Pre (SD)	Post (SD)		
Dynamic Condition ($N = 81$)				
Overall	2.57 (0.57)	3.99 (0.66)	17.53***	2.30
Tree	2.70 (0.74)	3.62 (1.03)	8.17***	1.03
Chloroplast	2.35 (0.78)	3.78 (0.90)	12.29***	1.70
MySystem	2.50 (0.74)	3.56 (0.97)	7.73***	1.23
Sun	2.44 (0.73)	3.85 (0.85)	12.23***	1.78
Energy Stories	2.63 (0.92)	4.29 (0.85)	13.39***	1.87
Static Condition ($N = 86$)				
Overall	2.63 (0.63)	3.67 (0.60)	13.93***	1.69
Tree	2.77 (0.76)	3.28 (0.75)	5.21***	0.68
Chloroplast	2.40 (0.70)	3.40 (0.88)	8.68***	1.26
MySystem	2.55 (0.85)	3.14 (0.82)	5.04***	0.71
Sun	2.59 (0.67)	3.65 (0.95)	8.52***	1.29
Energy Stories	2.70 (0.93)	3.98 (0.79)	11.53***	1.48

***$p < 0.001$.

Overall Gains. To assess how the dynamic and static conditions helped students link their understanding of energy transformation to other energy ideas in photosynthesis, we analyzed performance on the pre- and posttests. Pre- and posttest items required students to make connections between energy transformation and other relevant energy concepts in photosynthesis, such as energy storage and energy transfer. Table 6 presents the average knowledge integration scores and standard deviations on the pre- and posttest items.

After completing the photosynthesis unit, students in both the dynamic and static conditions showed significant improvement across all five items. Students in both conditions successfully integrated new ideas about energy transformation into their understanding of photosynthesis on the posttest. In particular, many students connected ideas about plants getting light energy from the sun to ideas about how plants use light energy to create glucose. For example, when asked to explain how the sun helps animals survive (the Sun item), a 7th-grade student gave a pretest response to this item using a string of ideas: "The sun helps animals survive by making food through photosynthesis." She used a scientific term, "photosynthesis," and provided an idea that photosynthesis is related to making food, but she failed to further articulate that the sun helps plants make food which is an energy source for animals. On the posttest, she made a scientifically valid link between the sun as the main energy source and the way plants use the sun to produce food, glucose: "When the sun is absorbed by the chloroplast in a plant's leaves, the chloroplast then produces glucose and oxygen so the animals can eat and breathe." These findings show that students in both conditions benefited from the visualizations of energy transformation and developed a more coherent understanding of the role of energy in photosynthesis from the pre- to posttest.

Effects of the Dynamic and Static Conditions. On the posttest, we found that students who interacted with the dynamic visualization of energy transformation significantly outperformed their counterparts in the static condition [$t(165) = 3.26$, $p < 0.01$] with a small to medium effect size of 0.43. The relatively smaller effect size may stem from the difference between posttest and embedded assessment items: items on the posttest required students to apply their ideas about energy transformation at the molecular level to the process of photosynthesis, whereas the embedded assessment items focus on the process of energy transformation at the molecular level. Students in the dynamic condition demonstrated their concrete understanding of the process of energy transformation in chemical reactions and linked these ideas about energy transformation to other energy concepts in photosynthesis. In contrast, most students in the static condition failed to articulate how light energy is used to create glucose and why glucose can be used as food for plants.

For example, in response to the Chloroplast item in the pretest, none of the students connected energy transformation in the chloroplast to the function of the chloroplast across the two conditions. On the posttest, 77% of the students in the dynamic condition made at least one scientifically valid link between ideas about energy transformation and the main function of the chloroplast. One student in the dynamic condition explained that the "chloroplast is an organelle that produces glucose with light energy, water, and carbon dioxide. The light breaks up the water and carbon dioxide molecules and then the molecules recombine [to] make an oxygen molecule and a glucose molecule."

In the static condition 47% of the students successfully integrated their understanding of energy transformation with the functions of the chloroplast. For example, one student in the static condition said "they [chloroplasts] get light energy from the sun to make glucose for the plant." This student left out the molecular processes of energy transformation to further explain the main function of the chloroplasts.

Energy Stories. To gain more insight into how students make connections between energy transformation and other energy concepts in photosynthesis, we examined changes in scientifically valid links students made from the pre- to posttest Energy Stories. Energy Stories are explanatory narratives that document students' cumulative, integrated understanding of energy concepts (Ryoo & Linn, 2010). This new item extends prior knowledge integration assessments (Liu et al., 2008; Liu, Lee, & Linn, 2010; Lee & Liu, 2010) and is designed to capture more complex connections between students' repertoire of ideas and to track student progress in greater detail than was the case for previous assessments. In this study, Energy Stories asked students to integrate their ideas about energy sources, energy transformation, energy storage, and energy transfer and write a story about how plants use sunlight to grow. We specifically examined students' integrated understanding of how energy is involved in photosynthesis, particularly their connections between ideas about energy transformation and other energy ideas, such as energy storage and energy transfer, in photosynthesis.

Consistent with findings from the prediction note and overall pretest there were no significant differences between the two conditions on the pretest Energy Stories [$t(165) = 0.49$, $p = 0.63$]. Only 30% of the students in both conditions were able to make one scientifically valid link between energy concepts. Most students who did make a link between energy ideas focused on ideas about energy transfer, a topic that was introduced in grade 6 as part of instruction about food webs. For example, 26% of students in both condition identified the energy transfer link by saying that "when an animal eats the plant, the animal will get the energy from the plant." Only 9% of the students in each condition noted that light energy gets transformed into a different form of energy (Energy Transformation link) and that energy is stored in glucose (Energy Storage link). None of the students in either condition explained how light energy is converted into chemical energy at the molecular level in their Energy Stories (Energy Transformation Molecular Level link).

On the posttest Energy Stories compared to the pretest, students in both the dynamic and static conditions made significantly more valid connections among energy transformation,

Table 7
Scientifically valid links students made in each condition on the posttest Energy Stories

Link Type	Link Pre (SD)	Link Post (SD)	t	Cohen's d
Dynamic Condition ($N = 81$)				
Energy Transformation	0.09 (0.29)	0.74 (0.44)	12.00***	1.74
Energy Transformation Molecular Level	0.00 (0.00)	0.52 (0.50)	9.44***	1.47
Energy Storage	0.08 (0.28)	0.41 (0.49)	5.82***	0.83
Energy Transfer	0.26 (0.44)	0.64 (0.48)	6.39***	0.83
Static Condition ($N = 86$)				
Energy Transformation	0.11 (0.32)	0.74 (0.44)	11.66***	1.64
Energy Transformation Molecular Level	0.00 (0.00)	0.23 (0.43)	4.95***	0.76
Energy Storage	0.10 (0.30)	0.21 (0.41)	2.24*	0.31
Energy Transfer	0.26 (0.44)	0.64 (0.48)	6.15***	0.83

*$p < 0.05$.
***$p < 0.001$.

energy storage, and energy transfer concepts and expressed more coherent understanding of the different roles that energy plays in photosynthesis (Table 7). There were no differences in links about energy transformation or energy transfer between the dynamic and static conditions. However, students in the dynamic condition, compared to the static condition, were significantly more likely to make a link about energy transformation at the molecular level in explaining how energy flows during photosynthesis in their Energy Stories [$t(165) = 3.83$, $p < 0.001$, $d = 0.60$].

For example, 52% of the students in the dynamic condition linked energy transformation at the molecular level in their Energy Stories by explaining how chemical reactions take place during energy transformation in photosynthesis. One student said: "The chlorophyll in the chloroplasts of the plant captures the Sun's light energy. The light energy is used to break up the molecules of carbon dioxide and water that the plant absorbs into smaller molecules. Without the broken molecules, the plant could not make glucose, so the plant needs light to survive. In another part of the chloroplast, the broken-up molecules are chemically combined to create a sugar called glucose and oxygen, which the plant gets rid of. This chemical combining is called photosynthesis. The plant uses most of the glucose in its cellular processes, but it stores some of it for later use. When a rabbit eats the plant, it absorbs the stored glucose and uses it in its cellular processes. This occurs over and over again, so that every organism gets its energy from the Sun." This student articulated abstract concepts about the role of light energy in starting the chemical reaction processes in the chloroplast by illustrating how light energy is used to split molecules which are later recombined to form glucose. The student also linked this unobservable phenomenon of energy transformation to energy transfer during photosynthesis by identifying how animals get energy from glucose by eating plants.

By contrast, only 23% of the students in the static condition made a link about the energy transformation at the molecular level in their Energy Stories. Students in the static condition explained that plants use light energy to create glucose, but they did not integrate details about exactly how this process happens using light energy in the chloroplast in their Energy Stories. For example, one student said, "A plant gets its energy from the sun's light. The sun's light energy is absorbed by the chloroplast to produce glucose and sugars (or energy) for the plant which ends up in a consumer, or animal.'' As shown in this example, many students in the static condition did not articulate why plants need light energy for photosynthesis and what happens to light energy during photosynthesis.

In addition, students in the dynamic condition, compared to the static condition, were significantly more likely to link ideas about energy storage in their Energy Stories [$t(165) = 2.80$, $p < 0.01$, $d = 0.44$]. Forty-one percent of the students in the dynamic condition were able to link the information about energy transformation learned in the dynamic visualization to their ideas about where energy goes after the transformation occurs. Many students in the dynamic condition successfully explained that during chemical reactions, ''energy is stored in glucose'' and ''plants use glucose to get energy'' as food ''to grow and live.'' For example, one student explained that ''10% of the sun's light energy is absorbed by the chloroplasts in the plant's leaves. The light energy splits apart water and carbon dioxide in the chloroplast. The former water and carbon dioxide molecules combine to form glucose. This is chemical energy which the plant can use to grow. Extra glucose is stored in the plant. When a rabbit eats the plant, it obtains 10% of the energy contained in the plant. This energy helps the rabbit grow.'' This student explained how light energy is used to make glucose and how light energy is transformed into chemical energy as well as how glucose is becomes an energy source for the rabbit, indicating that she/he had integrated understanding of energy flow during photosynthesis.

By contrast, only 21% of the students in the static condition linked ideas about energy storage. Most students in the static condition did not connect their ideas about plants using light energy to create glucose to how energy stored in glucose is used by plants or other animals in their Energy Stories. For example, one student in the static condition wrote a story saying that ''Plants go through a process called photosynthesis. Which is when sunlight gives of [off] energy to the plant which hits the chloroplasts and carbon enters through the air and water enters through the roots. Once that all happens they all collide together which makes food for the plant which is called glucose. Now if an animal eats the plant the energy is then passed down to the animal.'' This student was able to articulate how plants use light energy to create glucose and how energy is transferred from the plants to other living organisms, but he did not explain where energy goes after it is transformed and did not articulate why plants create their own food, glucose, during photosynthesis.

In summary, students in the dynamic condition took advantage of the dynamic representations of energy transformation to gain insight into the role of light energy in photosynthesis. The students in the dynamic condition could link molecular processes of energy transformation to the mechanism of photosynthesis to explain the flow of energy in photosynthesis. Although the two conditions had identical illustrations, explanations and interactivity and the static illustrations presented the same ideas as the dynamic representations, the students in the static condition were less successful in linking their observations to related energy ideas presented in the unit. These results demonstrate that dynamic visualizations of molecular processes can help students understand the abstract, unobservable concepts of energy transformation in photosynthesis. The results also suggest that a clear understanding of energy transformation contributes to an integrated understanding of how energy flows in photosynthesis.

Limitations

The findings of this study show that using dynamic visualizations in inquiry instruction, as compared to static illustrations, significantly improved middle school students' understanding of energy transformation in photosynthesis and their ability to make connections between molecular views of photosynthesis and observable events. Our study focuses on middle school students' understanding of photosynthesis and might not generalize to other age levels or science topics. We studied only two teachers with previous experience using technology for science. The results might not generalize to less experienced teachers. Further research is needed to determine how teacher experience and subject matter impacts the benefit of dynamic visualizations in teaching and learning science. Additionally, because the visualizations were embedded in a curriculum using the knowledge integration framework, it is possible that dynamic visualizations would be less successful when embedded in instruction designed using a different framework. Finally, although we carefully selected 15 snapshots from the dynamic visualization to document the process of energy transformation for the static condition, we might have been able to select a better set of images that could alleviate some of the confusions students encountered. In addition, there might have been a better way to create a static condition using different sets of images to help students develop a more integrated understanding of energy transformation.

Conclusions

The results of this study clarify the value of using the dynamic visualization, as compared to static illustrations, for depicting unobservable scientific processes. We found that the dynamic visualization gave students a more accurate view of the unseen, complicated process of energy transformation at the molecular level in photosynthesis than static illustrations. Static illustrations were less effective than the dynamic visualization in helping students understand how light energy gets transformed into a different form of energy while chemical reactions between molecules occur during energy transformation. This is consistent with other studies that establish the advantage of dynamic visualizations in understanding chemical reactions (Ardac & Akaygun, 2005; Chiu & Linn, 2008; Jones et al., 2001; Marbach-Ad et al., 2008; Sanger et al., 2000; Williamson & Abraham, 1995; Yarden & Yarden, 2010).

We found that students in the dynamic condition provided more detailed explanations about how aggregates of molecules interact during energy transformation in photosynthesis than did students in the static condition. Students in the static condition needed to animate the static illustrations in order to visualize the interactions. This led some students in the static condition to develop new non-normative ideas about chemical reactions during photosynthesis; some inferred that molecules are absorbed by the chloroplasts after being split during photosynthesis.

The results also show that students in the dynamic condition demonstrated a significantly more integrated understanding of photosynthesis than their counterparts in the static condition. Students in the dynamic condition were able to link their understanding of energy transformation at the molecular level to the observable aspects of photosynthesis. In contrast, the link between these two levels of photosynthesis was rarely identified by students in the static condition. In particular, students who used the dynamic visualization developed a sophisticated view of energy flow during photosynthesis. They made connections between the way light energy is transformed into chemical energy, the storage of energy in glucose, and how plants use glucose as an energy source. Students in the static condition failed to explain where energy goes after energy transformation occurs. The effect size for the difference between the two conditions is in the small to medium range ($d = 0.44$), consistent with the arguments of Kesidou and Roseman (2002) and Stern and Roseman (2004) who said that limitations in understanding energy transformation in photosynthesis prevent learners from comprehending how energy flows in an ecosystem. Our study provides evidence that explicit animation of energy transformation using dynamic visualizations can be more effective than static illustrations in helping students integrate their ideas about the role of energy in photosynthesis, including where plants get energy, how energy is transformed, and where energy goes.

The results of our study suggest that successful instruction using dynamic visualizations requires not only specific design features that provide detailed depictions of scientific phenomena, but also instructional support to help students distinguish new ideas presented in the visualizations from their existing repertoire of ideas to overcome deceptive clarity (Kali & Linn, 2008; Linn et al., 2010; Linn & Eylon, 2011). In this study, static illustrations were embedded in the same carefully designed instruction as the dynamic visualization, using the knowledge integration framework, and provided students with opportunities to compare their predictions to their observations. Although the dynamic condition was superior to the static condition in teaching energy transformation in photosynthesis, it is important to note that students in the static condition also significantly improved their understanding of energy transformation and photosynthesis.

For both conditions, the knowledge integration processes of eliciting ideas, adding ideas, distinguishing ideas, and reflecting on ideas contributed to improving students' coherent understanding of energy transformation during photosynthesis. The results of the assessments embedded in the photosynthesis unit document how students made sense of the visualizations and capture the process of students' knowledge integration. The prediction note showed that students in both the dynamic and static conditions started with equal and limited understanding of energy transformation in photosynthesis. The reflection note completed immediately after the interactions with the dynamic and static materials showed that students in both conditions were able to add new ideas about the complex process of energy transformation. As mentioned earlier, the ideas added in the static condition were less accurate than those in the dynamic condition; yet students in the static condition also showed significant improvement in their understanding of energy transformation from prediction to reflection questions. The delayed reflection note showed that students benefited from comparing ideas with their peers and considering additional alternatives in both conditions. These results are consistent with other studies showing that the sequence of activities implemented using the knowledge integration framework, including making predictions and distinguishing ideas, can overcome the potential for deceptive clarity in visualizations (Chiu & Linn, 2011; Linn et al., 2010; Linn & Eylon, 2011) and reduce the possible confusions associated with dynamic visualizations addressed in previous research (Mayer et al., 2005; Morrison & Tversky, 2001; Rieber, 1989). These findings indicate that with appropriate instructional support to promote knowledge integration, such as asking students to predict and reflect on their observations, both dynamic visualizations and static illustrations can better support students in developing a coherent understanding of abstract, difficult concepts of scientific phenomena than when used in a stand-alone format.

In conclusion, the results of the study show the added value of dynamic visualizations and their potential advantages over static illustrations in teaching energy transformation in photosynthesis to middle school students. When students can explore how the molecules move and interact with each other during energy transformation in the dynamic version, they gain more insight into energy transformations in photosynthesis and make more connections between energy ideas in photosynthesis than when they navigate between discrete illustrations. The insights gained from the dynamic visualization enable students to develop a coherent and integrated understanding of energy in photosynthesis. They have the potential to communicate unobservable events that are difficult to infer from textbook illustrations.

These findings underscore the importance of a design that involves the inquiry process, such as making predictions and distinguishing ideas, to take advantage of dynamic visualizations in science curriculum materials. Further research is needed to clarify how dynamic visualizations can enhance middle school students' ability to develop an integrated understanding of abstract concepts of energy across scientific disciplines. Future research should also explore alternative instructional approaches to help students distinguish ideas, such as the frequency of generating explanations while interacting with visualizations.

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Notes

[1]All students' responses were directly taken from the assessment. Therefore they may retain students' spelling and grammar mistakes.

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