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Chapter 7
The Role of Self-monitoring in Learning Chemistry with Dynamic Visualizations

Jennifer L. Chiu and Marcia C. Linn

Introduction

We explore how and why monitoring of one's own progress strengthens learning from scientific visualizations. Visualizations of unobservable phenomena can play a central role in improving understanding of science topics including chemical reactions, electricity, and photosynthesis. Visualizations typically target difficult, complex ideas and require students to interpret novel representations. To take advantage of visualizations, we argue that students need cognitive understanding of the phenomena as well as metacognitive skills to guide their own learning.

Students need to integrate multiple representations of scientific phenomena to form robust conceptual understandings in science, but typical instruction often leaves them with isolated ideas (Clark et al. 2008; Davis 2003; Kozma 2003; Linn 1995; Linn and Eylon 2006, 2011). For example, in chemistry, students use symbolic representations to solve stoichiometry problems, recognize macroscopic changes in laboratory experiments, and see molecular pictures in textbooks, but have difficulty putting them together. Furthermore, learners bring their own ideas from everyday experiences. Learners have many ideas about concepts such as phase change based on observing water boiling, snow melting, and food freezing. Incorporating a molecular and symbolic account of observable phenomena like phase change requires well-designed visualizations and guidance (Johnstone 1991).

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Many students develop procedures to work chemistry problems without a conceptual understanding of the chemical reaction (Nakhleh 1993). Students interpret chemical equations, such as $2H_2 + O_2 \rightarrow 2H_2O$, as letters and numbers instead of seeing this as shorthand for breaking and forming bonds between atoms with changes in energy. Because students learn chemical reactions through chemical equations, students associate these symbolic equations with math problems. As a result, students have trouble integrating representations of chemical equations and reactions and developing coherent understanding (Krajcik 1991).

Value of Visualizations

To promote integrated understanding of chemistry, dynamic, interactive visualizations can clarify misunderstood ideas such as bond breaking and bond formation. Dynamic visualizations refer to external representations that demonstrate changes in scientific phenomena, often with user-controlled interactive capabilities. Dynamic visualizations can illustrate normative ideas about chemistry and support learners to test their own ideas. Visualizations of chemical reactions allow students to interact with phenomena at the molecular level (Chang et al. 2010; Pallant and Tinker 2004; Williamson and Abraham 1995). They facilitate connections among ideas by providing multiple, linked representations of phenomena at molecular, observable, and symbolic levels (Kozma 2003; Wu et al. 2001).

Design of Visualizations

Successful scientific visualizations are difficult to design and generally require iterative refinement based on trials with student users (McElhaney 2010; Tate 2009). Refinements often increase the comprehensibility of the visualization and reduce extraneous information (Linn in press).

Research demonstrates benefits from dynamic visualizations on chemistry learning (Hoffler and Leutner 2007), but impacts of visualizations are uneven (Tversky et al. 2002). Students may add ideas but not connect them to their existing ideas. Analysis of studies featuring dynamic visualizations revealed that students can add ideas but often other, isolated ideas remain in students' repertoires (e.g., Lowe 2004).

Some authors point out that learning from visualizations is difficult because the visual complexity overwhelms novices (Mayer 2001; Paas et al. 2003). Others note that large numbers of students are able to master complex visual environments and apply ingenious scientific practices while learning to play videogames (Steinkuehler and Duncan 2008). The problem may not be so much that visualizations are cognitively overwhelming, but that students' learning practices, patience, and criteria for understanding vary depending on the context and the goal of the visualization. Engaging metacognitive skills such as monitoring progress and seeking help from peers in academic settings may enhance the impacts of scientific visualizations.

Curricular Supports for Visualizations

Research demonstrates that embedding dynamic visualizations in instruction designed to promote knowledge integration helps students take advantage of visualizations and form complex and integrated understanding of science (Chiu 2010; Linn et al. 2006, 2010; Lee et al. 2009; McElhaney 2010; Tate 2009). In this chapter we explore how successful instruction helps students monitor and regulate their understanding when learning with dynamic visualizations (Azevedo et al. 2005; Lowe 2004; Schnotz and Rasch 2005).

Successful instruction prompts students to explain their interpretation of a visualization in words. For example, transcripts of students working with *eChem* suggested that the visualizations facilitated self-explanations that helped refine links among ideas of chemical structure and bonding (Wu et al. 2001). Ainsworth and Loizou (2003) found that students learning about the circulatory system generated more explanations and higher quality explanations when prompted to explain static diagrams instead of text. In addition, the students in the diagram condition significantly outperformed students in the text condition on content assessments. They hypothesized that prompting explanations with diagrams helps maximize memory resources, encourages learners to integrate new information into their existing mental models, and may motivate students to actively process ideas.

These results suggest that students may need more guidance as well as specific types of guidance to monitor their understanding of dynamic visualizations within technology-enhanced environments (Tversky et al. 2002). Research suggests that self-monitoring skills have a large impact on how students interact with and how much students learn from dynamic visualizations (Lowe 2004; Moreno and Mayer 2007; Zahn et al. 2004). For instance, learners who made large conceptual gains in computer-based environments with text, diagrams, and animations monitored their understanding nearly twice as much as learners who made small conceptual gains (Azevedo et al. 2005). These monitoring activities included becoming aware that they did not understand (judgments of learning), expressing that they have learned something similar in the past (feelings of knowing), and questioning their understanding (finding gaps in knowledge). In contrast, learners who did not make large gains spent little time self-monitoring and instead engaged in activities such as copying information or looking through the environment without specific plans or goals.

Recent studies demonstrate the effectiveness of support within technology-enhanced environments to promote self-monitoring skills (Azevedo 2005; Graesser et al. 2005; White and Frederiksen 2005) and call for scaffolding tools within science inquiry environments to support ongoing explanation and self-monitoring of understanding (Quintana et al. 2005). For example, Aleven and Koedinger (2002) used an intelligent instructional software program, a "Cognitive Tutor," to scaffold explanations for students studying high school geometry. They found that students with explanation support from the cognitive tutor outperformed students with only problem solving support. They suggest that facilitating explanations with the cognitive tutor helped learners integrate visual and verbal forms of information and discouraged students from developing superficial procedural knowledge.

Role of Metacognitive Skills

Although metacognition can refer to a wide variety of processes (Georghiades 2004; Schoenfeld 1992), most agree that metacognition involves some form of self-knowledge and self-regulation (Brown 1987; Flavell 1987; Schraw 1998; Zimmerman 1990). Metacognitive expertise involves knowledge about oneself as a learner, such as knowing what you do or don't know, as well as knowing how you learn various types of material (Brown 1987). Metacognitive self-regulation includes planning, monitoring, testing, revising, and evaluating one's activities (Baker and Brown 1984).

Research demonstrates that supporting students' development of self-knowledge and self-regulatory skills can improve student performance across many domains (Palincsar and Brown 1984; Scardamalia and Bereiter 1991; Schoenfeld 1985). These metacognitive processes are especially important and beneficial for inquiry science learning in technology-enhanced environments (Quintana et al. 2005; White and Frederiksen 1998, 2005) and chemistry (Kaberman and Dori 2009; Rickey and Stacy 2000).

Activities that help students develop metacognitive skills include modeling thinking processes for students and scaffolding students to engage in these processes (Collins et al. 1991). Computer environments can promote metacognitive expertise by prompting students to participate in planning, monitoring, regulation, and reflection processes (Quintana et al. 2005). For instance, students can be prompted to reflect upon their current thinking or to reflect upon their project success (Davis and Linn 2000). Computer environments can also model these types of processes by providing metacognitive agents whose role is to provide planning, monitoring, and synthesizing advice (White and Frederiksen 2005).

To investigate the contribution of self-monitoring, we use two approaches. In one approach we measure self-assessments and investigate the effect of prompts for explanations of visualizations on self-knowledge. In the second approach, we study patterns of revisiting visualizations. We examine the impact of explanation prompts that ask students to distinguish ideas on student choice to revisit the visualizations. Prompts to distinguish ideas are designed to help students actively sort, refine, and reflect upon their understanding. By explicitly asking students to explain their ideas and assess their understanding, we purposefully guide students in activities that evoke metacognitive skills. Both of these approaches clarify the role of self-monitoring on learning from visualizations.

Chemical Reactions Unit

The *chemical reactions* curriculum unit was designed by a partnership of teachers and researchers supported by the Technology-Enhanced Learning in Science (TELS) Center for Teaching and Learning. *Chemical reactions* is a 5-day curriculum unit (approximately 5–6 h of class time) that unites the Web-based Inquiry Science Environment (WISE) from the University of California at Berkeley (Slotta and Linn 2009), and dynamic visualizations (Molecular Workbench) from the Concord Consortium (Fig. 7.1). These dynamic visualizations include computational models

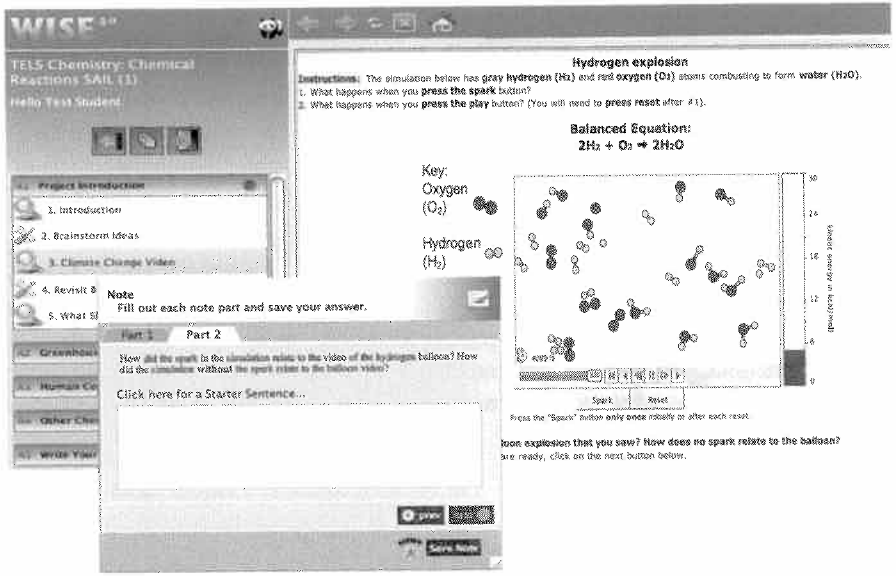

Fig. 7.1 In the WISE *chemical reactions* project, students use the inquiry map on the left to guide inquiry, use visualizations to add and test ideas, and use pedagogical tools such as online discussions, drawings, and embedded explanations to help distinguish ideas

of atomic interactions during chemical reactions. The unit leverages students' existing ideas about global warming and the greenhouse effect and connects ideas about chemical reactions to these phenomena.

The topic of chemical reactions provides a rich context for our studies. Students typically experience difficulty connecting molecular and symbolic representations of chemical phenomena (Ben-Zvi et al. 1987; Gabel 1999; Johnstone 1991; Kozma and Russell 1997). For instance, students have trouble relating the subscripts and coefficients of symbolic representations to the number and arrangement of atoms and molecules. Learners often interpret 2CO as two carbon atoms and one oxygen atom instead of two molecules of carbon monoxide. Many interpret CO_2 to refer to one disconnected carbon atom and one molecule of O_2. Understanding the symbolic representation of atoms and molecules serves as a gateway to learning complex phenomena and connecting the everyday world to the molecular world. Students who understand symbolic equations of chemical reactions on a molecular level can make robust connections to ratios of dynamic molecules interacting instead of simply doing math. However, textbooks rely heavily on symbolic representations, and teachers are often unaware of the gaps in their students' knowledge.

Knowledge Integration Perspective

The partnership designed the chemical reactions unit following the knowledge integration perspective. The knowledge integration perspective emphasizes learning as a process of building on existing knowledge by adding, sorting out, and refining views from various contexts and experiences (Bransford et al. 1999; diSessa 1988; Linn 1995; Linn and Eylon 2006, 2011). Knowledge integration is based on decades of research from developmental, sociocultural, cognitive, and constructivist perspectives demonstrating that learners have diverse perspectives and alternative ideas about science (e.g., diSessa 1988; Hammer and Elby 2003; Linn and His 2000; Minstrell 1992). The knowledge integration perspective values students' rich repertoires of ideas and encourages learners to build upon and sort out their ideas. Students engage in knowledge integration by using evidence to distinguish their alternative ideas and refine their understanding of scientific phenomena. To help students make connections among representations, the designers took advantage of design principles and patterns for knowledge integration (Kali 2006; Linn et al. 2004). They implemented the four processes of the *knowledge integration pattern* to structure the overall activities:

Eliciting Ideas

The first knowledge process involves eliciting student ideas, often in the form of predictions. Many studies show the value of making predictions and building on student views (e.g., Linn and His 2000). It is essential to identify all of the student ideas so that they can be connected to other valid ideas or reconsidered in light of new ideas. When students identify their ideas, they can get feedback on them and compare them to other ideas. For example, if students believe that, in a chemical reaction, all the molecules break into atoms and then reconnect but fail to articulate this view, they may end up keeping it in their repertoire. To elicit ideas about the connections between chemical reactions and climate change, we asked students questions such as: "How do chemical reactions relate to the environment?" We asked students to draw their predictions about how atoms and molecules would interact in the visualization.

Adding Ideas

Eliciting students' existing ideas brings prior knowledge about a subject or concepts to the forefront. Instruction can then add new, normative ideas to learners' existing frameworks. In chemical reactions, the visualizations add new ideas. It is common for typical instruction to focus solely on adding ideas, leaving students with isolated and incoherent views of science (Linn and Eylon 2011).

The unit adds ideas about combustion using videos of a hydrogen balloon combusting and guiding students through visualizations of hydrocarbon combustion reactions where they manipulate different ratios of reactant molecules to form products. Students add ideas about climate change by conducting experiments using a NetLogo visualization of the greenhouse effect (Fig. 7.2). Students watch videos, explore simulations, and make their own models. Students also learn about the many

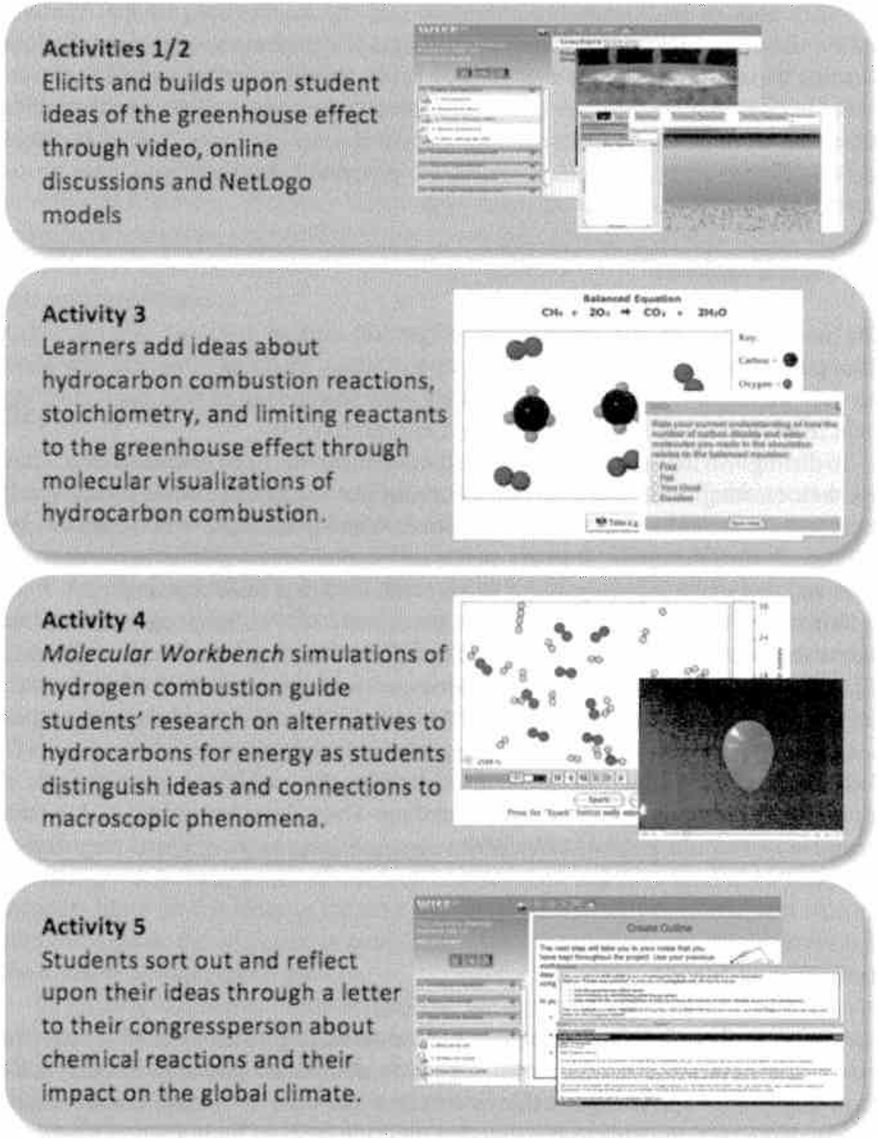

Fig. 7.2 The different activities within the *chemical reactions* project guide students along the knowledge integration pattern

everyday uses of hydrocarbon combustion and the implications of the resulting carbon dioxide in the atmosphere. The unit guides students to make connections between these representations and to consider the future of hydrogen as a fuel.

By juxtaposing student ideas with new ideas, the pattern elicits metacognitive skills such as monitoring understanding. In addition, by starting with eliciting ideas and then adding ideas, the pattern sets up the process of distinguishing ideas.

Distinguishing Ideas

The next process in the knowledge integration pattern involves distinguishing among new ideas and the existing repertoire of ideas. Students often add new ideas but only use them in the context where they were learned rather than distinguishing them from their other ideas or using them in everyday life.

To distinguish ideas, students explore the chemical reactions visualizations. They test their existing ideas. They take snapshots of the sequence of bond breaking and bond formation depicted in the visualizations. When interacting with the molecular workbench visualizations, learners make and explain connections between symbolic and molecular representations using embedded explanation prompts.

When experimenting with the NetLogo climate model, they make and refine their own models of the greenhouse effect. They develop criteria for evaluating ideas (i.e., evaluating their own explanations, critiquing explanations of their peers, or seeking evidence to support or refute their ideas). In addition, students are asked to explain how chemical reactions relate to the environment.

All these distinguishing ideas and activities have the goal of engaging students in assessing and refining their own understanding. Thus, these activities involve both cognitive and metacognitive skills. When distinguishing ideas, students may realize they need additional evidence and return to the visualizations to resolve a question.

Reflecting on Ideas

The fourth process involves reflecting and consolidating ideas to build a coherent view of the topic. Ultimately students need to coordinate productive ideas, prior knowledge, and experience to achieve coherent and durable scientific understanding. To encourage students to put together their ideas about hydrocarbon reactions, climate implications, and alternative fuels, the chemical reactions unit guides them to write a letter to their congressperson and to participate in an online class discussion where they debate alternatives. This activity has a metacognitive component: as students fit their ideas together they may monitor their understanding, identify gaps in their knowledge, and seek additional information.

In summary, the knowledge integration pattern guides students in both cognitive and metacognitive activities. Learners use cognitive skills to gain new ideas and develop criteria for comparing these new ideas to prior knowledge. Learners use metacognitive skills to evaluate their understanding. Together these skills help them distinguish more productive and relevant ideas from less productive ideas. Learners use self-knowledge to judge their understanding and to monitor and regulate their learning. For instance, students could add ideas about conservation of mass in chemical reactions but realize that they do not understand how conservation of mass connects to their existing ideas about reactions on a molecular level. Learners can act upon this realization and decide to use strategies such as reviewing information to refine connections. Students then reflect upon these connections among ideas, examine alternatives, and possibly revise or test their new connections. Metacognitive activities include spontaneously generating explanations, reflecting, self-assessing, and self-monitoring.

Impact of the Unit

Prior studies of the *chemical reactions* module demonstrate the effectiveness of the curriculum as a whole to help high school students understand chemical reactions. Students significantly improve from pretest to posttest. They make more connections among representations and ideas about limiting reactants, conservation of mass, and the greenhouse effect compared to students from the same teacher receiving typical, text-based instruction (Chiu 2010). Additionally, the students outperformed students on the year-end assessments administered to similar students at the same schools who did not participate in the TELS curriculum (Linn et al. 2006). These results have been replicated across years and across contexts (Chiu 2010).

A longitudinal analysis showed that students significantly improve upon their own scores from posttests to year-end assessments administered months after the unit (Lee et al. 2009). These results suggest that students develop coherent ideas and remember what they have learned months after study of the unit. The finding that students build on the ideas in the unit and integrate ideas from subsequent instruction throughout the semester is consistent with the emphasis on metacognition in the knowledge integration pattern.

To investigate the role of metacognition, we report on two studies. The judgment of learning study investigated how learners judge their understanding before and after generating explanations. The revisiting study explored the conditions under which students return to the visualization while learning.

Study 1: Judgments of Learning from Visualizations

To investigate the value of prompts for explanation of the visualizations, we documented students' judgment of their own learning before and after explanation prompts. We sought to characterize how students monitor their understanding in these sequences. Specifically, we wondered whether visualizations impact students' judgments of their learning and how prompting for explanations mediates this student understanding of visualizations. This study documented the value of explanation prompts to help learners and distinguish ideas.

Distinguishing Ideas by Eliciting Explanations

Prompting for explanations can help students distinguish their ideas in many contexts. Generating explanations that connect ideas about scientific phenomena can help students integrate new, productive ideas with existing knowledge (Chi et al. 1989). Successful students tend to spontaneously explain their ideas more often than less successful students (Chi et al. 1989). Explicitly prompting students to explain has been found to help students learn from scientific texts (Chi et al. 1994; Davis 2003) and benefit problem solving (Bielaczyc et al. 1995). Eliciting explanations can spur students to recognize conflicts, examine conflicting information, and refine their ideas (Chi et al. 1994).

Prompting students to distinguish ideas can be difficult in authentic classrooms. Students can respond to explanation prompts by repeating memorized phrases without analyzing possible gaps in understanding or checking for completeness of knowledge. For instance, learners can explain their understanding by saying that they understand (Davis 2003). However, well-designed prompts can spur learners to question their comprehension, realize inconsistencies in their ideas, and identify gaps in their views (Chi et al. 1989; Rozenblit and Keil 2002).

For example, Tien et al. (2007) prompted students to reflect and explain connections between macroscopic observations and molecular models of salt and sugar dissolving in water. As part of the Model-Observe-Reflect-Explain (MORE) pedagogical approach, college-level general chemistry students described their initial models of molecules dissolving (model), carried out laboratory experiments (observe), reflected upon their observations, and used their experiments to refine their ideas (reflect and explain). Of the 84 students participating at three different institutions, 35% had correct initial models of salt dissolution, 32% had accurate initial models of sugar dissolution, and 15% had correct models of both. After reflecting and explaining, a significantly greater proportion of students had correct models of the phenomena (80% salt, 52% sugar, 46% both) across institutions. Prompting students to reflect upon their ideas and explain connections among molecular and macroscopic representations helped students develop understanding of ionic and covalent dissolution.

Similarly, Davis and Linn (2000) investigated how explanation versus activity prompts affected middle school students' understanding of thermodynamics concepts within the Knowledge Integration Environment (KIE). Specific activity prompts asked eighth-grade students to think about different aspects of a project, such as "the letter says we need to…" or "the major claims of the article include…." Explanation prompts encouraged students to monitor their learning through planning (e.g., "Thinking ahead: To do a good job on this project, we need to…") and reflecting upon the activity (e.g., "In thinking about how it all

fits together, we're confused about…"). Explanation prompts were better than activity prompts in supporting students' integration of scientific principles into explanations, and for linking scientific principles to real-life experiences. Additionally, students who reflected upon ideas and "checked their understanding" were more likely to develop an integrated understanding of the project. Thus, prompting for explanations may help learners distinguish ideas and reflect upon their understanding. We use explanation prompts to help learners distinguish ideas and reflect upon their knowledge.

Judging Learning and Knowledge Integration

Knowledge integration includes evaluating one's understanding. Studies show that learners both overestimate (Koriat 1997) and underestimate (Hyde et al. 1990) their abilities. Research suggests that learners who initially overestimate their understanding increasingly underestimate their abilities after repeated study and testing cycles (Koriat et al. 2002). Students who are better able to assess their understanding tend to be more successful learners (Wiediger and Hutchinson 2002).

Studies have identified many factors contributing to learners' difficulties assessing their understanding, such as the nature of the assessment task, subject-matter knowledge, the surrounding learning environment, and motivation. For example, Zoller et al. (1999) studied how college chemistry students assess themselves on midterm exam questions. Zoller et al. found that students' judgments of learning and professors' assessments did not significantly differ on questions that assessed straightforward cognitive skills, such as simple recall or recognition of facts. On open-ended items that required students to explain their understanding or rationale, students tended to overestimate their ability as compared to their professors.

Impacts of Judging Learning

Supporting students to assess their understanding and reflect on their progress can help students learn scientific inquiry (White and Frederiksen 1998) and computer science (Bielaczyc et al. 1995). However, these studies also demonstrate the intricacies of promoting self-assessment with learners. White and Frederiksen (1998) found that students involved in reflective self-assessment processes improved on inquiry measures as compared to students without the self-assessment prompts. Students in the self-assessment group had differential gains on conceptual measures depending on achievement level. A variety of factors contribute to students' self-assessment, and their resulting action or inaction can impact the effectiveness of these kinds of supports. Capturing how students evaluate their understanding in authentic classroom contexts can help researchers develop successful and meaningful ways to support student learning

Several studies show a connection between evaluating one's understanding and generating spontaneous explanations. A Chi et al. study (1989) found that successful problem solvers recognized when they did not understand more often than less successful students. Some investigators report that successful students appear to be awakened by the realization that they do not understand and use this observation to seek ways to reconcile their ideas (e.g., Baker and Brown 1984). Thus, asking students to evaluate their own understanding may help them identify weak links in their repertoire.

Judgment of Learning Participants

High school chemistry students ($n=173$) completed *chemical reactions* in the fall semester. Students attended two diverse public schools in California. Students at both schools previously covered most topics of chemical reactions, balancing equations, and limiting reactants. Students went through the unit in pairs.

Two teachers participated in the study. Teacher 1 ran the project with five classes, comprised of two honors and three regular classes. This teacher, affiliated with the TELS center, was a member of the design partnership. This was the teacher's third experience running this project. The other teacher, teacher 2, ran the project with two regular classes in another high school in the same district. The teacher had not previously run the *chemical reactions* unit but had run other TELS projects during the year.

Judgment of Learning Data Sources

The unit took approximately 1 week of 55-min classes to complete. Both teachers administered a paper pretest to individual students 2 days before the unit began, and a paper posttest the day immediately following the conclusion of the project. These tests included 13 free-response items that allowed students to create their own drawings and representations of chemical reactions. Items across tests were identical. The pretests and posttests asked *individual* students to rate their understanding of four different concepts: the greenhouse effect, limiting reactants, balanced equations, and the effect of heat on chemical reactions. These judgments of learning were multiple-choice, allowing students to rate their understanding as poor, fair, very good, or excellent. The self-assessment questions were dispersed among the other questions.

During the curriculum, pairs of students distinguished ideas from visualizations through embedded prompts after visualization steps. For example, after interactively making water molecules, a prompt asked students, "How did making water molecules in Molecular Workbench relate to the balanced equation?" Either before or after these explanations students assessed their own knowledge of the visualization and related concepts. Similar to the pretest and posttest, pairs of students rated their understanding of particular topics within the unit as poor, fair, very good, or excellent. These rating prompts targeted certain concepts; for example, after the

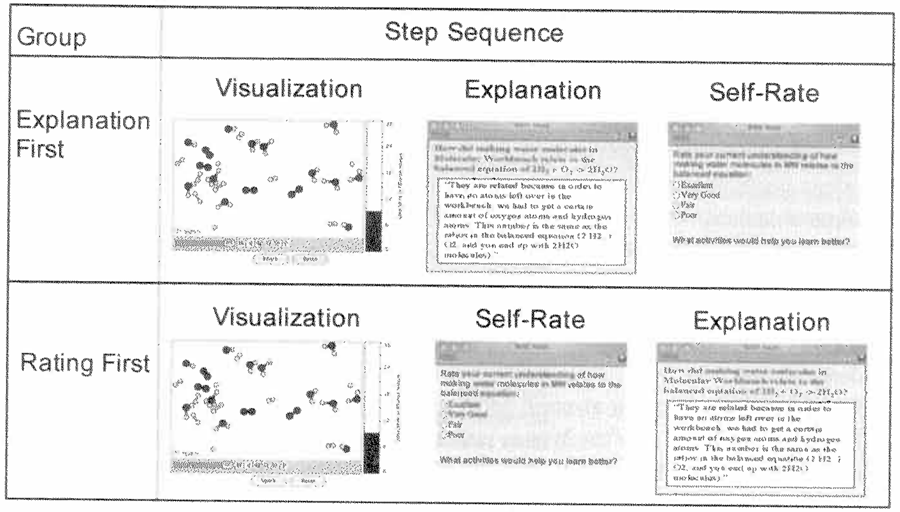

Fig. 7.3 In the judgment of learning study, the Explanation First group explained their understanding immediately after working with visualizations, and the Rating First group rated their understanding immediately after interacting with visualizations

same interactive water-making visualization, the rating prompt asked students, "Rate your understanding of how making water molecules in the visualization related to the balanced equation."

To investigate how students evaluate their learning surrounding visualizations and explanations, we varied the order of the judgment of learning and explanation prompts. We hypothesized that students would overestimate their understanding after viewing the visualizations. In contrast, we hypothesized that generating explanations would help students identify difficulties and result in more accurate assessments of learning. Although stimulating students to engage in self-monitoring may improve learning outcomes, since both groups engaged in judging their own learning, we hypothesized that both conditions would result in similar student progress.

Within each class, student pairs were randomly assigned to Explanation First or Rating First conditions. These two groups had the same curricular content, except the order of the explanation and rating steps were switched. The Explanation First group had explanation prompts immediately following visualizations and then rated their understanding in the next step. The Rating First group rated their understanding immediately following visualizations and then explained their understanding in the next step (Fig. 7.3).

Judgment of Learning Analysis

The scoring of pretests, posttests, and embedded explanation prompts identified the numbers of connections that students made among ideas, following the

Question: "How did what you had left over in the simulation relate to the ratios in the balanced equation, $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$?"
Prompt: "We had...left over. This relates to the balanced equation because..."

Knowledge integration level	Score	Description	Sample responses
Complex-link: Students understand how more than two science concepts interact in a given context	4	Elaborate two or more scientifically valid links among ideas relevant to a given context	"We had 1 oxygen molecule left over. This relates to the balanced equation because it shows the ratio of molecules that react. We started out with 2 methane molecules and 5 oxygen molecules, so we had one oxygen left over."
Full-Link: Students understand how two scientific concepts interact in a given context	3	Elaborate a scientifically valid link between two ideas relevant to a given context	"We had 2 oxygen atoms left over. This relates to the balanced equation because there was a 1:2 ratio of molecules that were created"
Partial-Link: Students consider relevant ideas in a given context	2	List normative ideas relevant to a given context	"We had 1 molecule of water left over. This relates to the balanced equation because there wasn't enough hydrogen"
No-Link: Students have non-normative ideas or links in a given context	1	List non - normative ideas or links	"We had none left over. This relates to the balanced equation because they're even"
Irrelevant: Students do not engage in a given science context	0	Off-task statements or blank answers	"I don't know"

Fig. 7.4 Example knowledge integration scoring rubric for embedded explanations

knowledge integration framework (Linn et al. 2006). In this study, higher scores represent more connections among representations, or more connections among ideas about chemical reactions, such as conservation of mass and limiting reactants. Across all items on both pretests, posttests, and embedded items, a score of zero represented no answer, one represented no link to relevant ideas, two represented a partial link to normative ideas, three represented a full link between normative ideas, four represented two full links among normative ideas, and five represented complex, multiple links among more than three normative ideas (Fig. 7.4). Researchers converted the pretest, posttest, and embedded student self-ratings into a numeric scale, where one = poor, two = fair, three = very good, and four = excellent.

Judgment of Learning Results

Teachers implemented the TELS curriculum in all classes with help from TELS researchers. Students worked through the project in pairs assigned by the teachers. Researchers randomly divided student pairs into Rating First or Explanation First groups on the first day of the project run.

One teacher missed 2 days of running the unit. In these classes, a substitute teacher and researcher helped students finish the last two activities. Across both schools, 99% of student groups finished four activities, and 86% of student groups finished all five activities. All self-rating and explanation prompts occurred in the first four activities. Students who missed either the pretest or the posttest were removed from the analysis. Researchers also removed students with no record of completing the curriculum unit. No significant differences on the pretest were found between those students removed from the analysis and those with complete data.

Pretest to Posttest Gains

Overall, students made significant gains from pretests to posttests across groups, replicating earlier results that the *chemical reactions* unit helps students make connections among representations in chemistry (Chiu 2010). Holding all other explanatory variables constant, the honors classes did significantly differ from the non-honors classes on the posttest. Honors students' knowledge integration levels were about three points (or three connections) above non-honors students' knowledge integration levels on the posttest.

On average, students made partial connections from the visualizations to traditional representations. For instance, in the second molecular visualization, students started with two methane molecules and five oxygen molecules and were instructed to form carbon dioxide and water. The explanation prompt following the visualization (Question 2) asked students how excess reactants in the visualization related to the balanced equation, $CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$. Most students correctly identified what was left over in the visualization (1 oxygen molecule or 2 oxygen atoms). Many students connected the "leftovers" with partial ideas about conservation of mass ("you can't gain or lose atoms, so the extra oxygen molecule couldn't be taken away"), ideas about balanced equations ("to balance the equation we don't need one oxygen molecule"), and limiting reactants ("there is not enough to make more"). Some students were able to connect the ratios of the balanced equation to what they had left over ("With the equation above there was 1 o2 [sic] left because we had 5. We needed only 4 so we subtracted 4"). No significant differences between groups were found on knowledge integration scores.

Judgments of Learning

In spite of giving similar explanations, the Rating First group consistently rated themselves as more knowledgeable than the Explanation First group (Fig. 7.5). Thus, prior to writing the explanation, the Rating First group had more confidence in their understanding than the Explanation First group had after writing their explanation. Ratings of understanding were higher after watching the visualizations than they were after writing the explanations, suggesting that the visualizations instilled a sense of deceptive clarity.

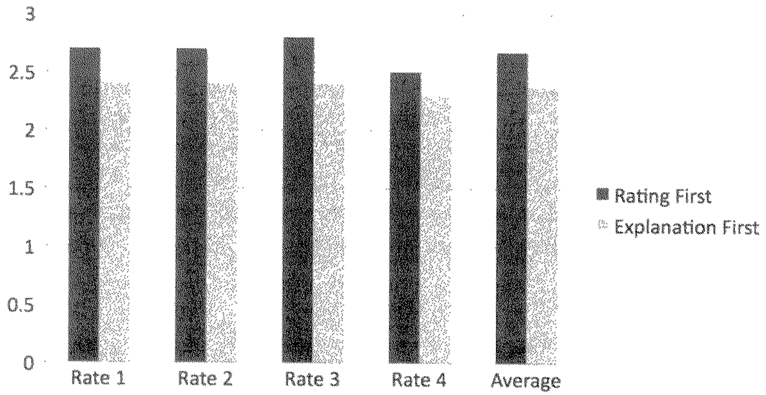

Fig. 7.5 Self-rating scores by Rating First and Explanation First group for each self-rating prompt and overall rating

Embedded Explanations and Judgments of Learning

As the curriculum progressed, concepts became more difficult, the explanation scores decreased, yet the judgments of learning in both groups stayed at roughly the same levels. The rating prompts asked students to judge their understanding of specific concepts such as limiting reactants. Interestingly, students judged their understanding similarly even though they were less able to use the concept in a knowledge integration explanation. Thus, although students' ability to integrate ideas decreased as the concepts became more advanced, students did not see themselves as becoming less competent (Chiu 2010). The ratings as the project progressed might reflect a sense of overall understanding of chemical reactions rather than a specific rating of understanding of the concept.

Group Differences

The Rating First group rated themselves as more knowledgeable than the Explanation First group. This indicates that the Rating First group's ratings were on average less accurate than the Explanation First group.

Pretest to Posttest Self-ratings

Students' individual judgments of learning increased from pretest to posttest, mirroring increases of pretest to posttest scores. Controlling for pretest ability, honors status, and project, students became more accurate at assessing their understanding from pretest to posttest, as measured by the residuals of regressing individual

self-ratings and pretest and posttest scores (Chiu 2010). Analysis of pretest to posttest self-ratings and explanations suggests that students on average rated themselves as more knowledgeable and were also more accurate.

Judgment of Learning Discussion

These results reveal the importance of self-monitoring for learning with dynamic visualizations. They suggest that visualizations are initially *deceptively clear* (Tinker 2009) but that this deceptive clarity can be overcome by encouraging students to monitor their progress.

Students rated themselves as more knowledgeable immediately after working with visualizations, and rated themselves as less knowledgeable after explaining what the visualization showed. This supports the idea that students may develop a false sense of competence or an "illusion of knowing" from working with visualizations (Keil 2006; Rozenblit and Keil 2002). Students interact with the visualizations and ignore details until they are prompted to explain what they observed. The findings resonate with studies that show that students become convinced they understand a visualization when they can recall only superficial features of what they have seen (i.e., Lowe 2004).

These results suggest three explanations for students' overestimations of understanding immediately after observing the visualization. First, students in the Rating First group may overestimate their knowledge because of the relative ease of accessing information learned from the visualization. In general, students report preferring visualizations to explanations (Corliss and Spitulnik 2008) and feel that visualizations are the best way to learn, possibly because the visualizations seem unambiguous.

Second, students in the Explanation First group have both more time and specific instruction to reflect before they rate their understanding. The explanation prompt gives students the opportunity to reflect on their understanding and identify gaps in their knowledge that could make their rating more accurate (Davis and Linn 2000). To illustrate, after the students investigate the dynamic molecular visualization of the hydrogen explosion, the explanation prompt asks students to relate the visualization to the macroscopic video of a hydrogen balloon exploding. One student pair in the Explanation First group responded that the visualization related to the balloon video "because it creates energy? I'm not completely sure." This student group rated their understanding as fair in the corresponding prompt. In contrast, a student group in the Rating First group rated their understanding as very good, yet responded, "I have no idea." Students in the Explanation First group may rate themselves as less knowledgeable than students in the Rating First group for reasons independent of the explanation item response. The greater time delay between the visualization and the rating prompt affords the Explanation First group an extended opportunity to think about the visualization and possibly appreciate its complexity (Dunlosky and Nelson 1992).

Third, students may have more experience judging their own performances on written tasks than on their interactions with visualizations. Students who rate themselves immediately after interactions with visualizations may overestimate their abilities because they do not have commensurate prior experience assessing their interactions with visualizations. Thus, a mediating step such as an embedded explanation prompt may give students a more valid reference point to judge their understanding.

Whatever the reasons for overestimation, students working with visualizations need help identifying what they do not understand and guidance to repair these deficits. These results help refine previous research suggesting that learners working with visualizations may be cognitively overwhelmed (Mayer 2001; Paas et al. 2003). Instead, students may have different criteria for their understanding of visualizations as compared to other instructional activities. Students need help in developing self-monitoring skills for evaluating their understanding of visualizations.

Knowledge Integration Patterns and Visualizations

These results suggest that the knowledge integration pattern contributes to learning with dynamic visualizations by helping students overcome deceptive clarity. The pattern adds value by helping students monitor their understanding through the development of criteria and refinement of their ideas and connections among ideas. Students interacting with visualizations may add ideas to their repertoire, but these ideas may be irrelevant and non-normative. Students need help to identify when ideas may be less fruitful or conflicting so that they can revisit and refine their understanding.

Prompting for Explanations

These findings show value for prompting for explanations. The value is consistent with the rationale for the knowledge integration pattern. Prompting for explanations encourages students to engage in knowledge integration by developing criteria, identifying gaps in their understanding, and distinguishing their ideas. The explanation prompt forces students to make their thinking visible, which "jars" them into realizing that they may not have understood the visualization as well as they previously thought. Giving an explanation requires students to develop criteria for their understanding that aligns with their criteria for explaining (e.g., "Am I capable of explaining? At what level/quality?"). By asking students to generate explanations, the knowledge integration patterns help students distinguish ideas and identify gaps in their understanding.

The act of generating an explanation forces learners to make their ideas explicit, which can help learners interpret dynamically presented material. Prompting for explanations can be seen as a form of a desirable difficulty for learning with visualizations (Linn et al. 2010). Generating an explanation prolongs the learning activity

and increases errors while ultimately improving outcomes. Prompting explanations also aligns with research in technology-enhanced environments that shows value for increasing generative processing (Moreno and Mayer 2007) or germane cognitive load (Paas et al. 2003) with visualizations. Explanation prompts may also benefit learners using dynamic visualizations by focusing attention on specific aspects of the phenomena. The explanation prompts may guide learners to connect the most relevant ideas to relevant prior knowledge (Lombrozo 2006).

To enhance student learning with visualizations, prompts can direct students to distinguish and analyze what they see. For example, students observing a visualization of an explosion that at first glance depicts slow molecules that bounce around and suddenly speed up may think they understand. The curriculum can prompt students to inspect the visualization more closely and help them recognize that the reaction starts when one of the reactants spontaneously dissociates. The resultant free radicals attack the other reactant, releasing energy that causes additional dissociations and reactions. By experimenting with different dissociation and activation energies via visualizations, students can gain a deep understanding of chemical reactions.

Prompting Self-monitoring

Consistent with their knowledge gains, individual students across all groups rated themselves as more knowledgeable on the posttest than on the pretest. These self-assessments were conducted off-line on paper and pencil, surrounding typical chemistry representations and concepts. Although students rated themselves as more knowledgeable on the posttest, the residuals from regression analysis decreased from pretest to posttest. This suggests that students became more accurate at rating their understanding (or became more critical of their understanding) after completing the *chemical reactions* unit.

These changes in individual self-ratings are consistent with the nature of the instruction. Students spent an entire week investigating and explaining chemical reactions in depth with the TELS curriculum. In addition, students assessed their understanding (albeit in pairs) throughout the curriculum. This kind of instruction can help students not only make connections in chemistry but also develop metacognitive self-knowledge and encourage refinement, revision, and reflection upon understanding, similar to other studies using technology to help students develop metacognitive skills (White and Frederiksen 2005).

The lack of a statistically significant distinction between groups on pre-to-posttest gains indicates that placing self-assessment prompts before or after the explanation prompts had no effect on students' knowledge integration score. This is consistent with the similarities of the groups in the amount of connections that students make among their ideas and among representations. Within the unit, even when provided with explicit prompts to connect ideas, students explaining their understanding on average made only partial connections among ideas on the knowledge integration scale.

Asking students to evaluate their understanding not only helps students make connections among ideas, but also appears to help students more critically and accurately assess their understanding. The combination of explanation and self-rating prompts helps learners become aware of gaps in explanatory knowledge about specific aspects of chemical reactions. These kinds of self-regulation skills are ultimately essential for guiding study practices.

Study 2: Prompting Explanations and Revisiting Visualizations

Even if learners accurately identify when they do not understand, they may or may not revisit valuable aspects of instruction to learn the material. In this study, we explored whether students revisited the visualizations and determined the instructional conditions that motivated this revisiting.

Studies demonstrate that learners will more often pick items to study that they deem as less well learned (Nelson et al. 1994) and will spend more time studying items that they think they will be less likely to recall (Mazzoni et al. 1990). However, this depends on the learning goals and study time of the student. Students with goals to minimize effort or study time may choose to spend more time going over items that they consider as easier to understand, whereas students with goals of overall comprehension may spend more time focusing on items that they perceive as more difficult (e.g., Linn and His 2000; Thiede and Dunlosky 1999).

Revisiting Study Rationale

Results from the first study raise questions about the role of prompting students to distinguish their ideas. The explanations helped students realize what they did not understand about the visualizations. However, if students know they do not understand a concept, they may or may not act upon these judgments to remedy gaps in their understanding. For instance, students could have decided to go back to visualizations after explanation prompts helped them identify what they do not understand. Alternatively, students could have simply gone to the next step in the project. We explored these questions by looking at logs of student actions.

Additionally, we were interested in the role of external feedback on students' development of self-monitoring and self-regulatory strategies with dynamic visualizations. Immediate feedback can be a powerful learning tool in both laboratory and classroom settings (Richland et al. 2007). Feedback can help students more accurately assess their understanding and provide targeted guidance to revisit visualizations. However, other research suggests that feedback can hinder monitoring skills (Mathan and Koedinger 2005; Moreno and Valdez 2005). Immediate feedback in computer-based environments may encourage mindless clicking instead of mindful interaction (Baker et al. 2008).

Thus, the revisiting study investigated the impact of immediate, external feedback and self-evaluation without feedback on student learning and monitoring with dynamic visualizations. We used the logging capabilities of WISE to investigate students' self-regulatory behavior as a result of feedback.

Revisiting Study Methods

Chemistry high school students in tenth and eleventh grades ($n=249$) from three teachers at one school completed the *chemical reactions* unit after covering chemical reactions concepts in textbook-centered activities. The curriculum, assessments, and scoring of items were the same as the self-assessment study.

Technology

The WISE 4.0 platform allows researchers to characterize how students progress through curricular units. The WISE interface documents when students click on any step, including when they begin writing an explanation, note, or self-assessment. WISE records how long they stay on each step, whether they revise an answer, and the nature of their subsequent activities. WISE also records how students interact with the visualizations – when they pause, replay, or change a variable for the model. These kinds of logging capabilities have been utilized in previous studies to examine the duration and quality of learner's interactions with visualizations or the computer-based environment (Buckley et al. 2004; McElhaney 2010).

To capture intentional activities, we analyzed when students chose to revisit a step out of sequence. WISE projects guide students' inquiry with the inquiry map, a persistent representation on the left side of the screen with steps for students to complete (Fig. 7.2). Although the curricular units are designed with activities and steps in certain sequences, students are free to choose any step at any time. Our classroom observations from previous studies revealed that students typically continue through the unit as designed. Students revisit steps when they realize that they are confused or do not understand something. We, therefore, regard these revisits as indicative of self-regulation, and analyzed the conditions that elicited this kind of behavior.

Conditions

Students were randomly assigned within classes to External Feedback (EF) and Self-evaluation No-Feedback (SE-NF) conditions (Fig. 7.6). In the External Feedback condition, the step after the visualization contained a multiple-choice question with feedback designed to focus the learner on a particular idea of the visualization. If the students correctly answered the question, they were told

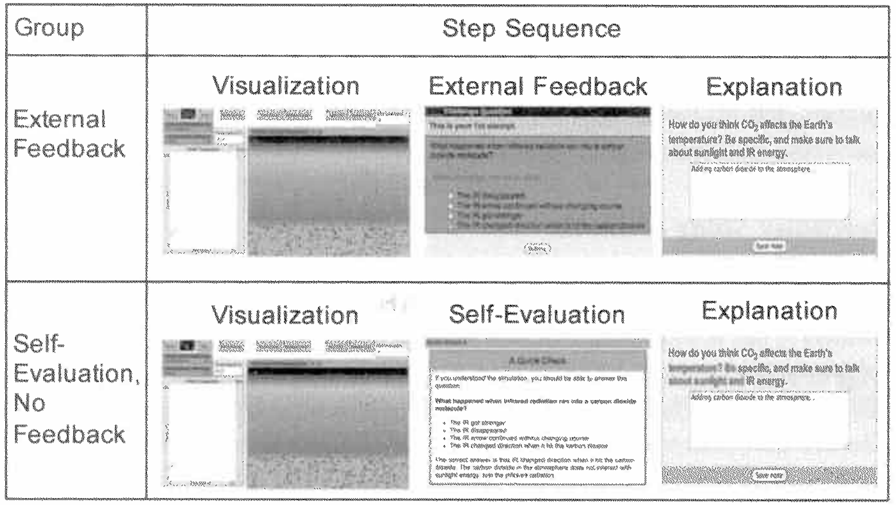

Fig. 7.6 External Feedback and Self-evaluation No-Feedback conditions for revisiting study

their answer was correct and were provided with a short explanation of the correct answer. If they answered incorrectly, students received feedback that their answer was incorrect and were guided back to the visualization with more detailed instructions about visualization. After revisiting the visualization, students could then retry the multiple-choice question with feedback. Students could not access later steps in the unit until they correctly answered the feedback question. Students who responded correctly moved to the next step where they were prompted to explain more complex phenomena in an open-ended response. For instance, a multiple-choice question with feedback asked students, "What happened when sunlight energy encountered a carbon dioxide molecule?" If the students answered correctly, they were able to go on to the next step that asks students to explain how carbon dioxide affects the Earth's temperature. The External Feedback treatment occurred twice after two greenhouse visualization steps in Activity 2.

Students in the Self-evaluation No-Feedback condition interacted with the same visualizations as the External Feedback condition. The step after the visualizations for the Self-evaluation No-Feedback condition consisted of the same question as the External Feedback condition (i.e., "What happened when a sunlight energy encountered a carbon dioxide molecule?"), but the text on the page said that to fully understand the visualization, one should be able to answer the question. The step encouraged students to revisit the visualization if they did not know the answer. This group had no feedback, the step was merely a text page, and students could access any step they wanted. The next step for the Self-evaluation No-Feedback group contained the same explanation prompt as the External Feedback group (i.e., "How does carbon dioxide affect the Earth's temperature?").

In subsequent activities, both student groups interacted with dynamic molecular visualizations and then were prompted to distinguish their ideas similar to the previous study. No feedback was given to either group on these activities.

Revisiting Study Results

Overall, students significantly improved from pretest to posttest across groups on the chemical reactions assessments. After controlling for pretest score, there were no significant differences between treatment groups (Chiu 2010). Classroom observations and analysis of the written explanations suggest that generating explanations reduces deceptive clarity. Explanation prompts encourage students to develop criteria to distinguish among their ideas. Students often revisit the visualizations to clarify their views. This finding is consistent with the design of the instruction using the knowledge integration pattern.

Role of Feedback

For the embedded assessments directly following the feedback/no feedback steps, students in the External Feedback condition did not score as well as those in the Self-evaluation No-Feedback, controlling for prior knowledge (Chiu 2010). Within the External Feedback condition, only 26% of the students answered incorrectly and were forced back to the visualization. There were no significant differences among students who answered incorrectly and those who answered correctly on pretest or posttest scores. Thus, the External Feedback was not frequently triggered and did not have a long-term impact on outcomes.

Revisiting Frequency

The designed curriculum has 57 steps in total. Counting the revisited steps, across all groups the mean of total visited steps was 64.1. Thus, there was an average of 8.2 (SD = 5.4) revisits per project. On average, students revisited 12% of the steps in the project. Students tended to revisit more steps in Activities 2–3 than in 4–5, possibly due to limitations of class time.

Revisiting Patterns

The most common revisiting pattern was from explanation steps to visualization steps. Figure 7.7 displays the steps students revisited throughout the unit. All of the steps in the unit are across the horizontal axis. Where students revisited "from," or the step where students went back from, is listed across the top graph by treatment

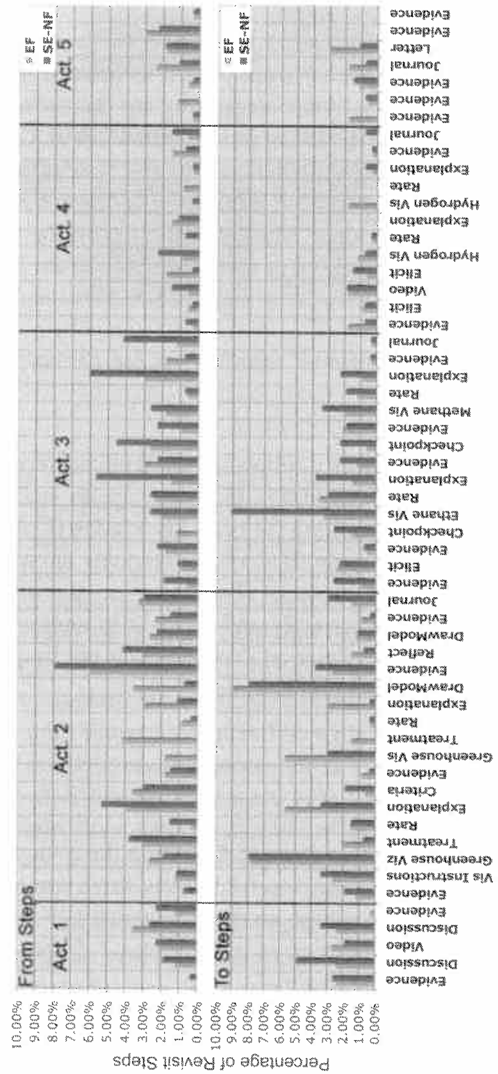

Fig. 7.7 Timeline of student revisits in the revisiting study. The top graph displays the steps from which students revisit for each treatment, and the bottom graph displays the steps to which students go when they choose to revisit a step

group. Where students revisited "to," or the step where they chose to go to, is listed along the bottom graph by treatment group.

Although most students follow the inquiry map to guide their interactions with the unit in a fairly sequential manner, the figure demonstrates that some students revisited after explanation steps, or drawing steps, or evidence steps. In the External Feedback condition, the most popular patterns were explanation to visualization (9% of the total revisits), the forced question to a visualization step (6%), and evidence steps to evidence steps (webpages of information and questions, without student interaction) (5%). For the Self-evaluation condition, explanation to visualization (11%), evidence to evidence (5%), and visualization to evidence (4%) were the most frequent revisiting patterns.

During Activity 2, although some of the student groups were forced to revisit the greenhouse visualizations based on their performance, the two groups had similar numbers of revisits to visualizations. During subsequent activities, students in the Self-evaluation condition revisited steps more than the students in the External Feedback condition (Chiu 2010). Students who were in the External Feedback group were half as likely to revisit the visualization as those in the Self-evaluation No-Feedback group.

Revisiting Study Discussion

Feedback and Dynamic Visualization

Both groups benefitted from writing explanations. The feedback treatment did not help students' immediate learning as measured by the embedded assessments. Thus, the External Feedback condition did not add value to the instruction. However, since most students succeeded on the multiple-choice questions, the feedback was not a major part of the instruction. A more challenging assessment may have benefitted students.

Students in the feedback condition were less likely to revisit the visualizations than were students who received no feedback even though students who gave incorrect answers were required to revisit the visualizations. Most students answered the question correctly and received feedback telling them their answer was correct accompanied by an explanation. Thus, feedback did not encourage them to revisit the visualization.

Revisiting Patterns

The most common revisiting pattern was from explanations to visualizations. These results suggest eliciting explanations may help students identify gaps in their knowledge and encourage students to revisit visualizations to remedy the gaps. This finding is consistent with studies showing that generative activities encourage students to revisit information (Linn et al. 2006).

Discussion

These studies illustrate the complexity of designing instruction to help students benefit from dynamic visualizations and the value of prompts for explanations. In the first study, we showed that visualizations can be deceptively clear as reflected in students' judgments of their understanding immediately after viewing the visualizations compared to their judgments after writing an explanation. In the second study, we showed that prompts for explanations motivate students to monitor their understanding and often revisit the visualizations to refine their ideas. We also found that providing feedback appears to short-circuit the process of monitoring performance and reduce the likelihood of revisiting the visualizations. These results underscore the importance of both cognitive and metacognitive skills for making sense of visualizations. Students need cognitive skills to interpret the scientific information. They need metacognitive skills to monitor their progress and determine when they need to fill gaps in their understanding.

Related findings for desirable difficulties support these results (Bjork 1994; Bjork and Linn 2006; Karpicke and Roediger 2008). Research on desirable difficulties identifies generation activities such as writing explanations as beneficial for learning. Generation activities prolong learning by asking students to articulate their interpretation of the visualization.

These results reinforce prior research on the effectiveness of prompting explanations in real-world classroom situations (e.g., Aleven and Koedinger 2002; Davis 2003; Davis and Linn 2000). They extend this research to illustrate how explanations can complement learning with dynamic visualizations. Prompting explanations enables us to illustrate how explanations can alert students to what they may have missed in the visualization and help students develop self-monitoring skills. Log file data provides evidence that explanations designed following the knowledge integration pattern spur students to take an active role in refining and sorting connections among their ideas by revisiting visualization steps.

These results support the value of the knowledge integration pattern for designing instruction featuring visualizations. The processes in the pattern engage both cognitive and metacognitive processes. Activities associated with distinguishing ideas and reflecting on progress seem most important for engaging students in monitoring progress and developing metacognitive awareness.

Visualizations require both cognitive and metacognitive skills due to their complexity and novelty. Developing the ability to monitor progress in understanding visualizations is likely to develop as students encounter visualizations across courses and topics. In addition, if instructional materials make consistent use of the same informative representations within a topic area, the importance of interpreting a novel visualization will diminish.

Overall, dynamic visualizations of molecular interactions present an exciting and novel instructional opportunity to study self-monitoring in chemistry. These results suggest that visualizations used without supportive surrounding instruction can result in students overestimating their understanding and spending too little time

analyzing the details of the visualization. Learners may completely overlook key concepts and ideas presented in visualizations. To learn effectively from visualizations, students need to engage in both cognitive and metacognitive skills.

Our research demonstrates that designing instruction using dynamic visualizations following the knowledge integration instructional pattern guides learners to elicit, add, distinguish, and refine their ideas. Specifically, the knowledge integration pattern guides students to monitor their understanding, realize gaps in their knowledge, and refine the ideas to their repertoire. This approach is particularly valuable because students gain both conceptual and self-monitoring abilities.

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